DREDGED MATERIAL RESEARCH PROGRAM

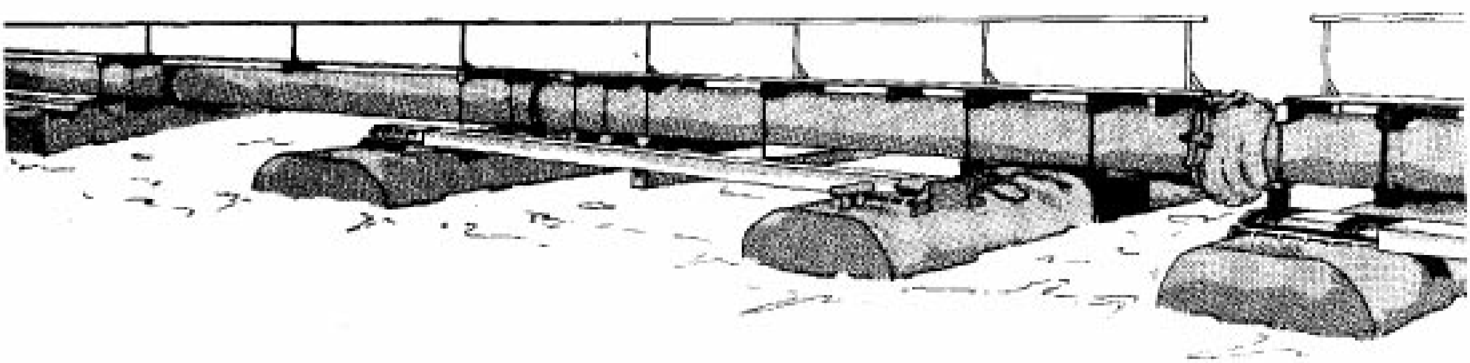
TECHNICAL REPORT D-78-44

EVALUATION OF THE SUBMERGED DISCHARGE OF DREDGED MATERIAL SLURRY DURING PIPELINE DREDGE OPERATIONS

by

Robert W. Neal, George Henry, Stephen H. Greene
JBF Scientific Corporation
2 Jewel Drive
Wilmington, Mass. 01887

August 1978
Final Report



Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under Contract No. DACW39-76-C-0112 (Neg.)
(DMRP Work Unit No. 6C08)

Monitored by Environmental Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO: WESEV

30 September 1978

SUBJECT: Transmittal of Technical Report D-78-44

TO: All Report Recipients

1. The technical report transmitted herewith represents the results of one research effort (Work Unit 6C08) initiated as part of Task 6C, entitled "Turbidity Prediction and Control," of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 6C, included as part of the Disposal Operations Project (DOP) of the DMRP, was concerned with investigating the problem of turbidity and developing methods to predict the nature, extent, and duration of turbidity generated by dredging and disposal operations. Equal emphasis was also placed on evaluating both chemical and physical methods for controlling turbidity generation around dredging and disposal operations.

2. Although there are still many questions about the direct and indirect effects of different levels of turbidity on various aquatic organisms, turbidity generated by dredging and disposal operations can be aesthetically displeasing. Therefore, regardless of the ecological effects associated with turbidity, it may be necessary, under certain conditions, to reduce the levels of turbidity that might be generated by a particular dredging or disposal operation. This study was concerned with evaluating the submerged discharge concept as a mechanism for reducing the turbidity levels generated in the upper water column by open-water pipeline disposal operations. Based on laboratory flume tests, four discharge configurations were tested and a diffuser was designed. Unfortunately, time and funding constraints did not allow field testing of this diffuser. However, mathematical scaling techniques were used to evaluate the effectiveness of the diffuser relative to a 20-degree submerged discharge configuration used as a baseline condition.

3. This study represents one of a series of reports on turbidity prediction and control. Other studies within Task 6C provide information on predicting the nature and extent of turbidity plumes generated by open-water pipeline disposal operations, silt curtains, and the

generation and flow of fluid mud dredged material. All research results from Task 6C are synthesized in Technical Report DS-78-13 entitled "Prediction and Control of Dredged Material Dispersion Around Dredging and Open-Water Pipeline Disposal Operations."

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report D-78-44	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EVALUATION OF THE SUBMERGED DISCHARGE OF DREDGED MATERIAL SLURRY DURING PIPELINE DREDGE OPERATIONS		5. TYPE OF REPORT & PERIOD COVERED Final report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert W. Neal George Henry Stephen H. Greene		8. CONTRACT OR GRANT NUMBER(s) Contract No. DACW39-76-C-0112 (Neg.)
9. PERFORMING ORGANIZATION NAME AND ADDRESS JBF Scientific Corporation 2 Jewel Drive Wilmington, Mass. 01887		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DMRP Work Unit No. 6C08
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE August 1978 13. NUMBER OF PAGES 232
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) U. S. Army Engineer Waterways Experiment Station Environmental Laboratory P. O. Box 631, Vicksburg, Miss. 39180		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Dredged material
Dredged material disposal
Dredging
Pipeline dredges
Turbidity
Underwater excavation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a study conducted to investigate the feasibility of using submerged discharge to control the turbidity generated when a pipeline dredge discharges a fine-grained dredged material slurry into open water. The program included a survey of field practices, literature survey, analytical investigations, and numerous flume tests.

The experimental investigation was performed at reduced scale in an 8-ft-wide

(Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued).

by 32-ft-long by 2.5-ft-deep test tank that was specially constructed for the program. Two series of tests were run: one in which a simple open pipe discharged dredged material slurry underwater and a second in which four different types of discharge processors, designed to reduce the discharge momentum, were tested and evaluated by comparing their performance with that of the open pipe. The influence of the following system parameters was examined: water type; sediment type; bottom type; solids concentration; and discharge velocity, angle, diameter or area, and height above the bottom.

The results of the experimental program demonstrated that striking reductions in turbidity can be realized with a submerged discharge processor that diffuses the flow, minimizes entrainment, and discharges the dredged material slurry close to the bottom. The proposed design incorporates a conventional conical diffuser and a radial discharge section.

A full-scale submerged discharge diffuser and a support and positioning barge were designed. An estimate was prepared for the costs of a detailed design and fabrication of a complete system.

Appendix A presents the results of a survey of Corps of Engineers and private dredge operators who have been involved in open-water discharge. Appendix B presents sediment concentration profiles for the baseline and processor tests.

THE CONTENTS OF THIS REPORT ARE NOT TO BE USED FOR ADVERTISING, PUBLICATION, OR PROMOTIONAL PURPOSES. CITATION OF TRADE NAMES DOES NOT CONSTITUTE AN OFFICIAL ENDORSEMENT OR APPROVAL OF THE USE OF SUCH COMMERCIAL PRODUCTS.

SUMMARY

The Problem

The U.S. Army Corps of Engineers was authorized by the River and Harbor Act of 1970 to conduct a comprehensive nationwide study concerned with the disposal of dredged material. The task of developing and implementing the study was assigned to the U.S. Army Engineer Waterways Experiment Station (WES) which established the Dredged Material Research Program (DMRP). The DMRP has as its objectives the development of more definitive information on the environmental aspects of dredging and disposal operations and the development of technically satisfactory, environmentally compatible, and economically feasible dredging and disposal alternatives, including consideration of dredged material as a manageable resource.

A common method of disposing of dredged material in hydraulic pipeline dredging operations is to discharge the pumped slurry into designated open-water disposal areas near the dredging site. Generally, this is done by allowing the slurry to discharge from an open pipe located above the water's surface. One effect is an increase in the turbidity and suspended solids in the water column. While the absolute impact of this turbidity on the environment is difficult to assess, it may be necessary to minimize its generation in certain situations.

Because of concern about potential environmental damage, open-water disposal has been severely curtailed in recent years. Such disposal is

controlled by the Federal Water Pollution Control Act Amendments of 1972 and guidelines subsequently developed by the Environmental Protection Agency and the Corps of Engineers (Federal Register). Those guidelines contain objectives associated with the "selection of disposal sites and conditioning of discharges of dredged material" which include the following:

a. Minimize, where practicable, adverse turbidity levels resulting from the discharge of material.

b. Minimize discharge activities that will degrade aesthetic, recreational, and economic values.

This study was conducted in order to investigate the use of submerged discharge as one means of conditioning discharges of fine-grained dredged material slurry in order to reduce or control the turbidity normally associated with open-water disposal.

Purpose and Scope

The specific objective of this work was to develop and evaluate equipment design, together with associated deployment techniques, for discharging fine-grained dredged material slurry beneath the water's surface in a manner that would effectively reduce the turbidity generated in the water column. The study consisted of three principal tasks:

a. Development of alternative submerged discharge concepts.

b. Evaluation of selected alternative concepts.

c. Evaluation of full-scale implementation requirements.

A variety of alternative configurations for submerged discharge were developed through close scrutiny and analysis of the mechanisms and processes involved in the generation of turbidity, supported by a review of the pertinent literature. In addition, a survey of dredge operators and Corps districts was conducted to obtain information about any prior experience with the use of submerged discharge in combination with hydraulic dredging.

In order to evaluate submerged discharge as a means of controlling turbidity, a laboratory test program was conducted. For this program, a test facility was designed and built for performing scaled experiments that simulated a variety of full-scale configurations. Two series of tests were run. In the first, called the baseline runs, experiments were performed using a plain open pipe discharging a sediment slurry under water. In the second, special discharge devices for controlling turbidity were attached to the pipe and evaluated by testing under a variety of operating conditions.

On the basis of the laboratory evaluation, one configuration of discharge device, a diverging nozzle or diffuser, was selected as a very promising candidate for full-scale evaluation. Full-scale designs of the diffuser were developed and dimensions and weights were determined for units suitable for 12-, 18-, and 24-in. pipeline dredges. In addition, the design of a barge for carrying and properly positioning the diffuser was developed.

The implications of utilizing the diffuser in a full-scale dredging operation were analyzed and described. In addition, an estimate of the cost to build a full-scale system was prepared and a program for full-scale demonstration was outlined.

Methods

In order to conduct scaled experiments, a complete test facility was designed and constructed. The principal elements were (a) a test tank 8 ft wide by 2.5 ft deep by 32 ft long with observation windows on both sides; (b) a slurry storage and conditioning system consisting of a 400-gal tank, circulating pump, and flow controls; (c) a filtered fresh water supply; (d) sampling equipment to characterize the dispersion of the dredged material during the tank tests. In addition, provisions were made for extensive photographic coverage, inasmuch as these records were an important source of primary data.

Using these facilities, a baseline test program was conducted to explore the physical characteristics of the dredged material dispersion that develops around open-water discharge configurations commonly used in hydraulic dredging operations. In addition, the performance data from this program were used as a reference base against which the performance of various submerged discharge designs could be compared and evaluated.

On completion of the series of tests utilizing a simple submerged open pipe (the baseline test program), another series of tests was run in order to evaluate the effectiveness of four different types of discharge devices (or processors) designed to reduce turbidity in the water column. The four devices tested were designated the shroud, the weir, the plenum, and the diffuser.

A matrix of tests was designed that would provide sufficient data to evaluate the processors and to compare their performance to that of a simple, open pipe as established in the baseline program. However, only the finally selected configuration (the diffuser) was subjected to the full battery of tests. The others were tested only enough to allow comparison among the four processors and to eliminate the less promising candidates.

After the diffuser was selected, a full-scale design was developed for 12-, 18-, and 24-in. pipeline sizes. In order to evaluate costs, a complete system, including the support barge, was designed and a detailed fabrication cost estimate was prepared for an 18-in. pipeline system. The estimate was based upon quotation from potential fabricators and suppliers.

Results and Conclusions

Regardless of discharge configuration nearly all of the dredged material slurry settles to the bottom to form a blanket of mud while a small amount remains in suspension in the water column. As the bottom layer thickens at the discharge point, it behaves like a density flow and spreads radially outward under the influence of gravity forces. It derives its increased density from the dispersion of suspended solids of which it is comprised. The mixture is referred to as fluid mud and its movement along the bottom as a mudflow. The mudflow system incorporates a fluid mud layer that flows along the bottom and a turbidity layer immediately above the mud layer. The moving mud layer supplies fluid mud to the headwave which is the advancing boundary of the fluid mud system. The turbidity layer is generated from turbulence in the head wave and at the shear boundary of the mud layer. The suspended solids concentration extends up to 10 g/ℓ in the turbidity layer and from 10 to about 200 g/ℓ in the fluid mud layer.

Submerged discharge is an effective technique for reducing the turbidity associated with the open-water disposal of fine-grained dredged material. Of the four processor models tested, the diffuser and the plenum were about equal in performance and were distinctly superior to the shroud and weir. The diffuser was selected over the plenum on the basis of practical considerations.

An open pipe, submerged and oriented vertically downward is very effective in reducing turbidity generation. Such a configuration should be considered seriously as a standard for comparison in any full-scale field evaluation of submerged discharge.

The performance of the diffuser is significantly superior to that of an open pipe discharging beneath the water, both in reducing turbidity and in controlling mudflow.

A submerged discharge system incorporating the diffuser can be designed that is both technically feasible and operationally practicable. The cost of a complete system including diffuser and discharge barge for an 18-in. pipeline dredge is approximately $212,000.

A method for making full-scale predictions of mud flow parameters based on the scaled laboratory tests was developed. This method, which will predict an upper limit value for the turbidity cloud height, mud flow height, and mud flow velocity for full-scale dredging situations, is based upon Froude scaling. It is necessarily limited in its application by the range of variables that were investigated in the laboratory experiments.

PREFACE

This report presents an evaluation of the submerged discharge concept as a means of controlling turbidity caused by the discharge of dredged material into designated open-water disposal areas during hydraulic dredging operations. The study was conducted by the JBF Scientific Corp., Wilmington, Mass., under Contract No. DACW39-76-C-0112 (Neg.), dated 29 June 1976, under Dredged Material Research Program (DMRP) Task 6C, "Turbidity Prediction and Control," Work Unit 6C08, "An Evaluation of the Submerged Discharge of Dredged Material Slurry During Pipeline Dredge Operations." The DMRP is sponsored by the Office, Chief of Engineers, U.S. Army, and is administered by the Environmental Laboratory (EL), U.S. Army Engineer Waterways Experiment Station (WES).

The study was conducted by Messrs. George Henry, Robert W. Neal, Stephen H. Greene, and Gary Bowers, JBF Scientific Corporation. The contract was monitored by Dr. William Barnard, Disposal Operations Project, EL, under the general supervision of Mr. Charles C. Calhoun, Jr., Project Manager, and Dr. John Harrison, Chief, EL. Mr. Calhoun was the Contracting Officer's Representative, and COL John L. Cannon, CE, was Contracting Officer.

Director of WES during the conduct of this study and the preparation of this report was COL John L. Cannon, CE. Technical Director was Mr. F.R. Brown.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.02832	cubic metres
cubic yards per hour	0.7645549	cubic metres per hour
degrees (angle)	0.01745	radians
feet	0.3048	metres
feet per second	0.3048	metres per second
gallons	3.7854	litres
gallons (U.S. liquid) per minute	0.003785	cubic metres per minute
inches	0.0254	metres
pounds (mass)	0.4536	kilograms
pounds (force) per square foot	47.88026	pascals
slug-feet per second per second	4.45	kilograms-metres per second per second

EVALUATION OF THE SUBMERGED DISCHARGE OF DREDGED MATERIAL SLURRY DURING PIPELINE DREDGE OPERATIONS

CHAPTER I: INTRODUCTION

Background

1. A common method of disposing of fine-grained dredged material in hydraulic pipeline dredging operations is to discharge the pumped slurry into an open-water disposal area near the dredging site. Generally this is done by allowing the stream to discharge from an open pipe located above the water's surface. In some instances, the open end may be fitted with a splash plate designed to deflect the stream and to disperse it over a greater area.

2. This practice affects the environment in several ways that may be potentially damaging. One effect is an increase in the turbidity and suspended solids in the water column. While the absolute impact of this turbidity on the environment is difficult to assess, turbidity generation can be minimized. The sediments themselves may be contaminated with such substances as pesticides or heavy metals. Organisms normally present in the water may be affected adversely by a reduction in sunlight, by interference with normal respiration, or by the presence of toxic substances with the sediments. In addition, the presence of large turbid plumes in an otherwise undisturbed body of water can be construed as degrading aesthetic, recreational, or economic values.

3. Because of the potential for environmental damage, open-water disposal of fine-grained material in estuaries has been severely

curtailed in recent years. Such disposal is controlled by the Federal Water Pollution Control Act Amendments of 1972 and guidelines subsequently developed by the Environmental Protection Agency and the Corps of Engineers.[1] Those guidelines contain objectives associated with the "selection of disposal sites and conditioning of discharges of dredged material" which include the following:

a. Minimize, where practicable, adverse turbidity levels resulting from the discharge of material.

b. Minimize discharge activities that will degrade aesthetic, recreational, and economic values.

Purpose

4. This study focuses upon the use of submerged discharge as one means of reducing or eliminating the turbidity generated by conventional open-water disposal of fine-grained dredged material slurry. It comprised three principal tasks:

a. Development of alternative submerged discharge concepts.

b. Evaluation of selected alternative concepts.

c. Evaluation of full-scale implementation requirements.

Scope

5. A variety of alternative configurations for submerged discharge were developed through close scrutiny and analysis of the

mechanisms and processes involved in the generation of turbidity, supported by a review of the pertinent literature. In addition, a survey of dredge operators and Corps districts was conducted to obtain information about any prior experience with the use of submerged discharge in combination with hydraulic dredging.

6. In order to evaluate submerged discharge as a means of controlling turbidity, a laboratory test program was conducted. For this program a test facility was designed and built for performing scaled experiments that simulated a variety of full-scale configurations. Two series of tests were run. In the first, called the baseline runs, experiments were performed using a plain open pipe discharging a sediment slurry under water. In the second, special discharge devices for controlling turbidity were attached to the pipe and evaluated under a variety of operating conditions.

7. On the basis of the laboratory evaluation, one configuration of discharge device, a diverging nozzle or diffuser, was selected as a very promising candidate for full-scale evaluation. Full-scale designs of the diffuser were developed, and dimensions and weights were determined for units suitable for 12-, 18-, and 24-in.* pipeline dredges. In addition, the design of a barge for carrying and properly positioning the diffuser was developed. The implications of utilizing the diffuser in a full-scale dredging operation are analyzed and described. In addition, the cost of building a full-scale system is estimated, and a program for full-scale demonstration is outlined.

*A table of factors for converting U.S. Customary units of measurement to metric (SI) units is found on page 17.

8. The baseline data were also utilized to develop a method of predicting mud flow parameters (cloud height, mud flow height, and head wave velocity) for a limited range of full-scale discharge configurations. The method is based upon Froude scaling of the model tests, and provides upper limit estimates of these parameters.

CHAPTER II: TECHNICAL DISCUSSION

Hydraulic Dredge Configuration

9. A hydraulic dredging operation utilizing open-water discharge for disposal of dredged material may be typified by describing a particular maintenance dredging project. The *William L. Guthrie*, a 16-in. cutterhead dredge, is utilized by the Corps of Engineers to maintain channel depth in various parts of the Gulf Intracoastal Waterway (GIWW). Over much of its length, the GIWW is located in inland waterways (rivers or canals) where dredged material is pumped into nearby diked areas for disposal. However, there are also many areas where the GIWW traverses bays and sounds that are protected by the barrier islands stretching along much of the coast of the Gulf of Mexico. In most of these areas, the dredged material is discharged into designated disposal areas in the open waters 1000 to 3000 ft to the side of the channel.

10. A typical project location for open-water disposal is Apalachicola Bay near mile 360 on the Florida coast. The channel may have silted enough so that water depths are 9 to 10 ft where nominal channel dimensions are 125 ft wide and 12 ft deep. For this project, the *Guthrie* might set its cutter head to dredge the channel to a depth of 14 ft. Proceeding along the channel, the *Guthrie* would swing on its spuds, cutting the full width of the channel in one pass.

11. Connected to the Guthrie is a 16-in.-diameter pipeline, supported on pontoon floats, through which the fine-grained dredged material slurry is pumped. The disposal area is about 1000 ft to the south, which means that the discharge pipeline may be around 1500 ft long to allow slack for relative motion between the dredge and the discharge-end pontoon.

Dredged Material Deposition

12. As the dredge moves more or less continuously along the channel, the entire string of discharge pipe must be moved periodically to advance the discharge point. For the most efficient operation, it would be desirable to move the pipe only as often as the progress of the dredge requires. However, the amount of sediment accumulating in the vicinity of the discharge point, particularly if mounding occurs, may require additional moves. An important consideration in the design of a system for submerged discharge is its potential effect upon the deposition of sediment in the disposal area.

13. The rate of accumulation of the fine-grained material will depend upon the nature and concentration of sediment in the slurry being discharged as well as the hydrodynamic conditions. This concentration will vary considerably as the depth of cut varies. In addition, the motion of the cutterhead is such that there is some overlap between cuts at the outer extremities of each swing across the channel. As a result, the concentration of the discharged slurry varies continually from as

much as 20 or even 25 percent solids by weight to virtually no solids. The long-term average concentration of sediments in a typical maintenance dredging operation would probably fall in the range of 10 to 15 percent.*

Mechanisms of Turbidity Generation

14. In current practice, it is common for the pipeline to be terminated simply as an open pipe, discharging almost horizontally at some distance above the water. As indicated in Figure 1, the slurry stream or jet exiting the pipeline is highly turbulent, entrains air as it enlarges, and is broken into individual drops in the outer portion of the jet. This action is illustrated in Figure 2. After penetrating the surface, most of the material remains in the jet, which continues to enlarge by entraining water. At the bottom, the sediments move away from the point of impact as a mud flow. However, a small fraction of the finer grained sediments remains suspended in the water column, creating turbidity.

15. Observations made in the field and in laboratory tank tests suggest that there are four mechanisms that generate turbidity in this process. The first is interaction between the water surface and drops or "pieces" of the slurry stream which have broken away from the jet. This interaction creates turbidity at and near the surface and is responsible for the visible part of the surface plume. In addition,

*Tests covered in this report are based on the percentage of solids by weight carried in the respective slurries. However, it should be noted that the usual practice in the dredging industry uses a percentage of solids by volume of in situ material removed relative to the volume of slurry pumped.

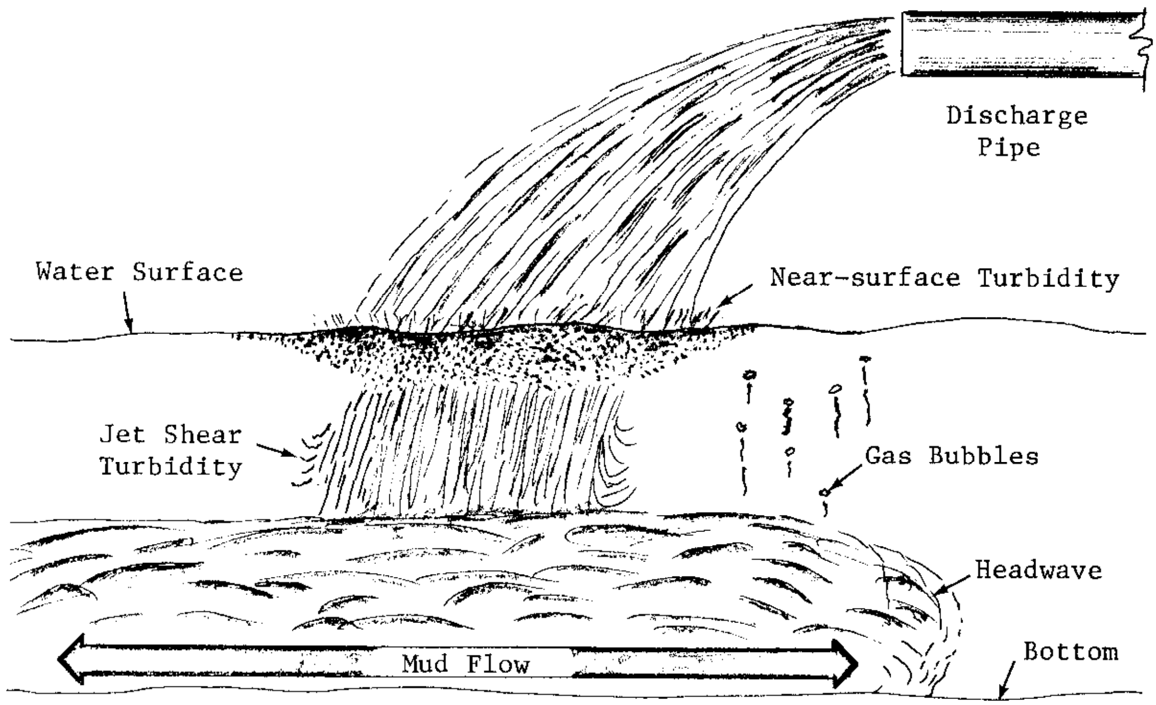


Figure 1. Slurry discharge jet

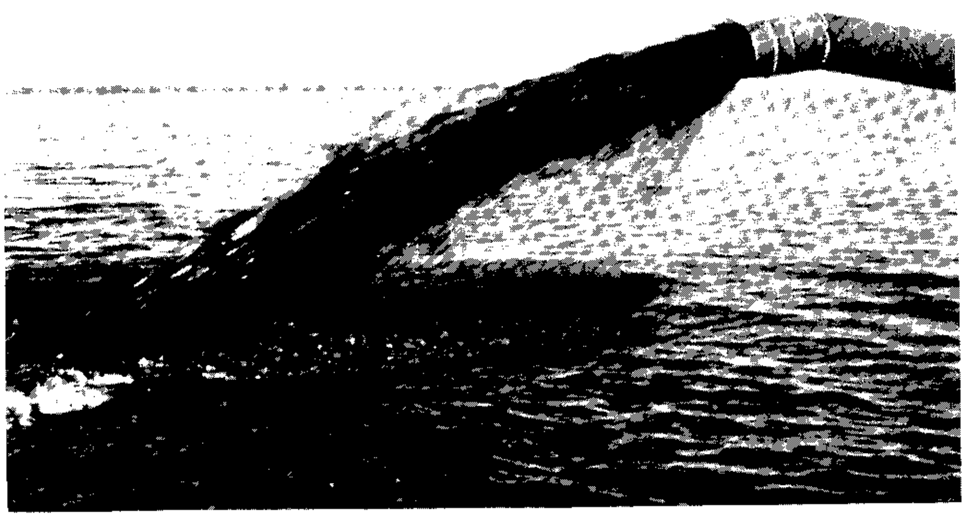


Figure 2. Typical above-surface discharge

depending upon the presence of organics or other constituents in the sediments, this action may also create froths and surface discoloration.

16. In the vicinity of the impact point and above the mud flow, there is a turbulent region in which finer sediments mix into the overlying water, creating turbid clouds that upwell into the water column. Depending upon the energy of the discharge stream and the depth of water, this turbid upwelling mixes upward and may even reach the surface.

17. A third mechanism is the shear between the descending jet and the surrounding water. For full-scale discharges, the Reynolds number in the submerged jet is probably sufficiently high for mixing to take place, which results in some dispersion of sediment into the water column.

18. A fourth mechanism which causes turbidity was observed during laboratory tests of submerged discharge. Sediments very commonly contain gases due to the decomposition of organic material. The gas can be entrained in the slurry stream and carried along in the pipeline. At the discharge some gas may escape the jet, but smaller bubbles near the center of the stream will remain in the jet and may be carried with the mud flow before being released. When a bubble is released, it carries fine sediment at the gas-water interface, and leaves behind a small turbid trail as it moves upward. This may not be a significant source of turbidity for above-surface discharges; however, for a submerged discharge, rising bubbles could become a major source of turbidity if not taken into account.

Mud Flow

19. The mud flow which carries most of the sediment away from the point of impact is, in fact, a density current. The suspension of fine-grained sediments behaves as if it were a denser fluid than the surrounding water. It therefore is capable of flowing under the influence of gravity with no appreciable mixing taking place. Several field observations[2,3] show that fluid mud may extend great distances (1000 to 2000 ft and more) from the point of discharge. Of course, the occurrence of a mud flow requires that sediments be fine enough to form a suspension. If not, the sediments will simply settle out at some distance from the impact point after their discharge momentum has been dissipated.

20. For a mud flow to occur and be sustained, the concentration of the suspension must fall within some fairly wide range.[4] Reported values of the upper and lower limits vary widely. No doubt, the limits depend upon a variety of factors, including in particular the type of sediment in question. Typical values for the lower limit are around 10 g/ℓ, and for the upper limit, values of 150 to 300 g/ℓ have been reported. It should be emphasized that these are not well established numbers; the important point is that there are upper and lower bounds on the concentrations at which mud flows may exist.

21. Below the lower limit, the sediment concentration in a suspension may still be great enough to be distinctly visible as a turbid cloud. This is of significance in laboratory testing because the turbid

cloud above the mud flow masks the true height of the flow and methods or techniques that do not depend upon visual observation must be employed to measure this height.

22. As the mud moves away from the impact area the coarse-grained material settles out of the mud flow and with time forms a sloped mound that is centered under the discharge point. Depending upon the type of sediment, its grain size distribution, and the period of consolidation, the concentration of the mounded mud can vary widely. Upon completion of pumping at a discharge location it can be as high as 300 g/ℓ (25 percent solids by weight).

Above-Surface and Submerged Discharge

23. An above-surface discharge arches downward under the influence of gravity until, at the point of impact with the water, its velocity is the vector sum of the discharge stream velocity and the vertical velocity due to gravity. The vector diagram, Figure 3, illustrates the case for a horizontal discharge 10 ft above the water surface, with a discharge velocity of 18 fps.

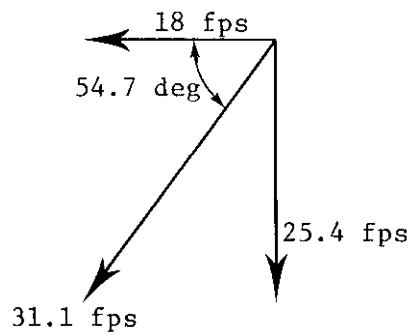


Figure 3. Jet vector diagram

24. For this example, the velocity of the jet when it hits the water surface is almost twice that at the discharge. Without taking into consideration any other factors, an obvious conclusion from this example is that submerging the discharge can reduce the jet velocity by a factor of almost two, which in turn represents a reduction in momentum of the jet by a factor of about three. These are significant reductions in velocity and momentum of the jet and are a direct result of simply submerging the end of the pipeline. Submerging the discharge also eliminates the interactions at the surface that generate significant turbidity.

25. In a few recent dredging projects, submerged discharge was used with some success to reduce the amount of turbidity generated. In these cases, no special equipment was used to control the discharge flow and the pipe was simply placed with its open end beneath the water surface. If the water is sufficiently deep, this method can be effective in preventing the turbidity from extending up to the surface. However, the velocity of the slurry on impact, though considerably reduced by the decreased height above the bottom and by entrainment of water in the jet, is still sufficient to generate considerable upward mixing of turbid water.

Design Goals

26. A mechanical device attached to the end of the submerged pipe can be designed which would reduce turbidity still further. Design goals

for such a device (referred to as a mechanical processor in this report) can be developed in part through consideration and analysis of the mechanisms that generate turbidity and of the characteristics of discharge jets of dredged materials. The principal goals are as follows:

a. The dredged material slurry should be discharged on or near the bottom since this is where it will eventually be deposited. The slurry should be contained on its trip to the bottom to eliminate mixing and water entrainment processes that generate turbidity in the upper water column.

b. The slurry should be discharged from the system at the lowest practical velocity. The object should be to establish at the discharge a density flow that is characterized by minimum water entrainment so that solids will remain close to the bottom and not be carried up into the water column, while still retaining sufficient momentum to prevent mounding in front of the discharge point. Since the entrainment coefficient is primarily a function of the velocity difference between the mud flow and the adjacent water column, the most direct control over the entrainment is to reduce the discharge velocity to very low levels.

c. The diffusion of the slurry momentum must be conducted within the confines of the mechanical system to prevent contact between the slurry and the water column before the slurry has been decelerated to an acceptable velocity level.

d. The turbulence level in the discharge flow must be controlled at a level that does not unduly enhance the entrainment process. The energy and momentum levels of the slurry flow are very high and require the use of dissipative devices to reduce turbulence to an acceptable level.

CHAPTER III: SYSTEM DESIGN STUDY

Introduction

27. The technical feasibility of the submerged discharge concept was established through the laboratory test model program that is described in subsequent chapters of this report. The objective of the system design study was to demonstrate the operational and economic feasibility of a full-scale system comprising the proposed processor design and the crane barge from which it is deployed. In the following sections design requirements for the processor and barge systems are reviewed, installation and operational procedures are described, cost estimates are presented, and a field demonstration program is proposed.

Design Requirements

28. The effectiveness of the submerged discharge system depends on control of the location and properties of the discharge jet, and on the ease with which the mechanical processor can be moved and manipulated. The detailed requirements that collectively satisfy these needs are outlined in the following sections.

System Components

29. The system will consist of a submerged discharge processor that conditions the flow prior to discharge and a support barge that positions the processor and attaches to the end of the dredge pipeline.

Location of Processor

30. The processor will be adjustable so that the submerged discharge will deposit dredged material slurry on or near the bottom. This short distance between discharge and deposition will afford minimum opportunity for upward mixing of the discharged flow with the water column.

Entrainment Control

31. The dredged mixture will not come in contact with the surrounding water until it reaches the location of the submerged discharge near the bottom. This guarantees that no entrainment, mixing, or attendant turbidity generation can occur until after the slurry is processed and ready for discharge.

Discharge Momentum Control

32. The momentum of the dredged slurry will be reduced in the processor so that upon discharge the mixing of the slurry with the water column will be minimized. This will be accomplished by reducing the flow velocity as it passes through the processor, thereby reducing the discharge velocity of the slurry.

Mounding Control

33. Equipment and procedures will be designed so that mounding of the discharged sediment under the processor will not be permitted to bury or plug the processor or otherwise interrupt the dredging operation before the pipeline would normally be moved to a new location.

Physical Limitations

34. The processor size and weight will be kept within practical limits to insure ease of handling and minimum downtime during moves from

one discharge location to another. The barge size will be limited to that required to manipulate the processor in a safe and stable manner.

Abrasion Resistance

35. The processor and attendant dredge plumbing design will minimize abrasion by proper design and the use of protective cover plates, liners, and shoes.

Sediment Gas

36. The processor design will employ a means of suppressing or eliminating the turbidity that is generated by the presence of entrained gas in the dredged slurry.

Anti-clogging

37. Normal amounts and sizes of debris and stones will not create blockage or cause the processor to be completely plugged. Not only could excessive blockage degrade the performance of the processor, but it could also cause the discharge pipeline pressure to increase sufficiently to create a safety hazard.

Operating Life

38. The submerged discharge system will be capable of an average operating life of dredging service. Its design will emphasize simplicity of operation and ruggedness of construction as the means of achieving high reliability.

System Operation

39. The submerged discharge system will be designed for maximum practical use by dredge operators. It will interface simply and compatibly with pipeline systems that are in current use. Dredge pipe and

fittings will be used throughout the barge plumbing system to eliminate the need for special parts. The design will insure ease of handling and adjusting the processor, and ease with which the barge is moved to a new discharge location.

Processor Design

Principle of Operation

40. The function of the processor is to reduce the velocity of the dredged slurry and to isolate it from the water column during the process of diffusion. The lower discharge velocity reduces the velocity difference across the mud layer - water column interface which in turn lowers the levels of fluid shear and turbulence at the interface as well as the rate at which turbid water mixes into the upper water column. The processor design must incorporate the characteristics of a flow diffuser in that as the dredged slurry passes through the device the cross-sectional flow area increases gradually until the desired velocity reduction is realized.

41. This can be illustrated by considering the flow through a conical diffuser (Figure 4). For a steady-state flow condition, the mass flow rate into the diffuser must equal that out. Consequently,

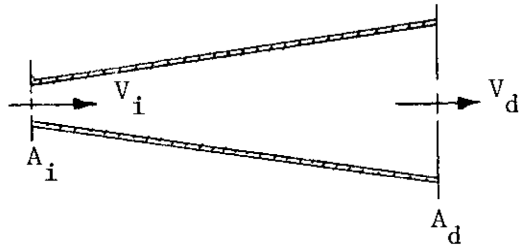


Figure 4. Conical Diffuser

$$(\rho VA)i = (\rho VA)d = w \tag{1}$$

where ρ = density of the slurry

A = cross-sectional flow area

V = velocity of slurry

w = mass flow rate of slurry

subscript i = inlet conditions

subscript d = discharge conditions

For an incompressible slurry equation 1 reduces to

$$(VA)i = (VA)d \tag{2}$$

or

$$\frac{Vi}{Vd} = \frac{Ad}{Ai} \tag{3}$$

Equation 3 says that the velocity reduction ratio is given by the area ratio. The above illustration is based on the assumption that the flow of slurry always fills the flow area and that the velocity is constant over any cross section (one-dimensional flow).

42. In the submerged discharge system, the flow path of the slurry is generally established by the physical arrangement of the major components. The processor will be lowered close to the bottom where it will be well below the elevation of the pipeline. The flow through the pipeline will be turned downward and will approach the processor inlet from above through a vertical section of pipe (Figure 5). Within the processor, the flow will be turned from the vertical to a near

horizontal direction so that it discharges in a radial flow pattern parallel to the bottom.

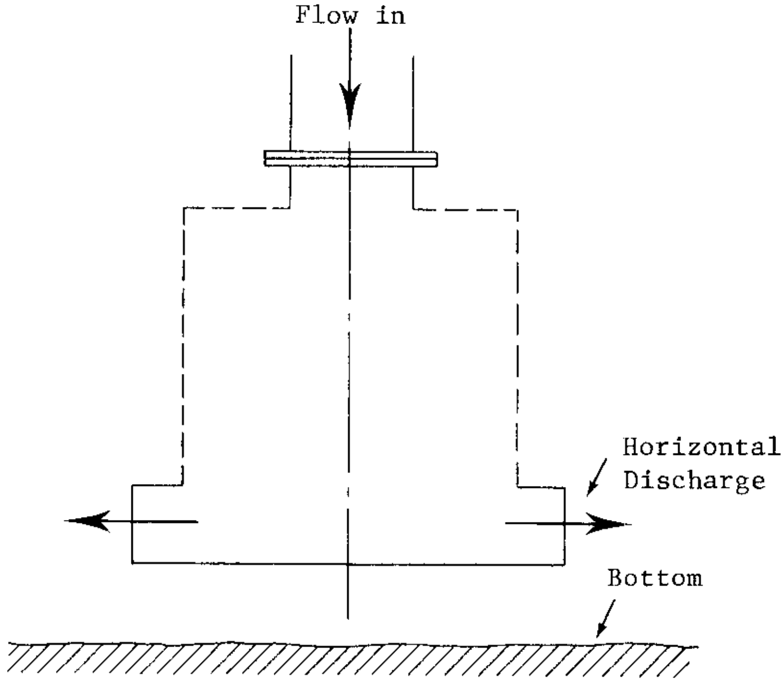


Figure 5. Flow schematic through processor

43. The velocity of the slurry can be reduced in the processor by either of two methods. In the first the slurry is allowed to jet into a relatively large volume where its excess kinetic energy is converted to frictional heat through the formation of an extremely intense and vigorous system of vortices, eddies, and large-scale turbulence. Since the thermal energy cannot be easily converted back to kinetic energy, it is lost to the environment and therefore creates an added load on the pumping system. Any large-scale turbulence present in the discharge flow increases the mixing of turbid water with the water column and represents another mechanism of turbidity generation.

44. In the second method the slurry is slowed down as it passes through the processor by gradually increasing the cross-sectional flow area along the flow path. During this process very little energy is lost (only to wall friction) if the diffuser is designed properly, and virtually all of the excess kinetic energy is converted to potential energy in the form of an increase in static pressure. Bernoulli's equation (equation 4) expresses the relationship that applies for one-dimensional flow conditions.

$$p + \frac{1}{2} \rho V^2 + \rho g h = \text{constant} \tag{4}$$

where

p = static pressure

V = slurry velocity

h = elevation above a datum

ρ = slurry density

g = gravitational acceleration

45. In this design the flow is guided gently so that there is no blatant source of flow turbulence. Consequently, at discharge the flow is quiet and free of large-scale turbulence if the entrance flow to the diffuser is of the same quality.

46. Based on these considerations, the low-loss diffuser design was chosen for the processor for the following major reasons: (a) the turbulence level in the discharge flow must be as low as possible to minimize mixing at the discharge flow/water column interface and (b) the processor must produce the lowest possible losses to minimize the additional load on the pumping system.

47. The concept for the processor design develops around a two-stage diffuser as shown in Figure 6. The first section is a 15-deg axial diffuser with an area ratio of about 4:1. The 15-deg angle is the largest expansion angle the flow can negotiate before separation sets in and causes the flow to jet. This section is faired into a combined turning and radial diffuser section that turns the flow radially outward. The flow is further diffused by increasing the radius and the circumference of the discharge opening. The radial section also has an area ratio of about 4:1 so that the overall expansion ratio of the processor is approximately 16:1. A pipeline flow velocity of 20 fps would be reduced to 1.25 fps at the discharge of the processor. The momentum of the flow would be correspondingly reduced by the same factor of 16:1.

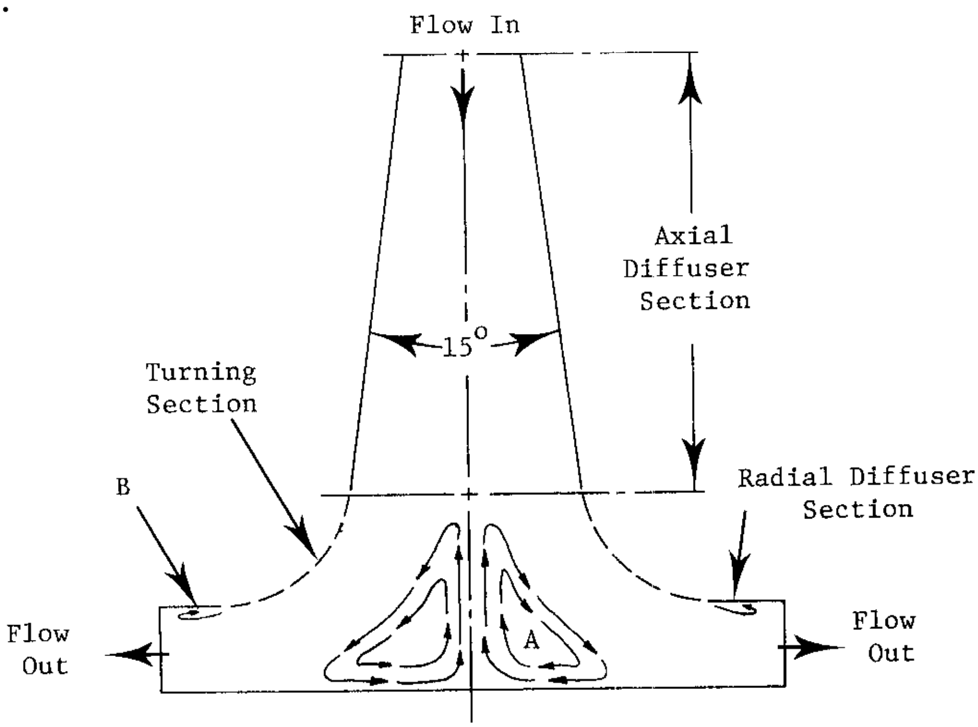


Figure 6. Schematic of the diffuser processor design

48. Because of limitations on the size of the processor, its shape will still create regions of separation in the flow through it. The turning section is designed with the shortest practical turning radius in order to keep the discharge diameter to about the same dimension as the overall length. As a result of the short turning radius there will exist a region of separation around the impingement point (A, Figure 6) wherein the flow readjusts itself to a smoother transition to radial flow. A smaller region of separation is also expected to occur at the end of the turn on the short radius streamline (B, Figure 6). These regions of separation tend to improve the flow pattern at the expense of energy lost in the eddies and vortices that form their cores. Generally, these losses can be eliminated by re-shaping the passage walls (e.g., adding an impingement cone) or by forcing the flow into the required pattern (e.g., with a set of guide vanes). The experience with such flow control devices in dredging operations is that continuous exposure to the abrasive slurry quickly wears the metal structures and the repetitive impact of stones and debris eventually destroys a structure that extends into the main stream. But these are design problems that can be minimized by more rugged structures and greater abrasion resistance. The drawback to guide vanes is that they act as a strainer for debris and stones and very quickly cause the processor to plug up, which introduces the hazard of overpressurizing the entire pipeline. Dredging operations must be halted while the unit is cleared of debris (no easy task) and

put back on line. Because they introduce a worse problem than the one they solve, guide vanes were ruled out of the processor design.

Full-Scale Design

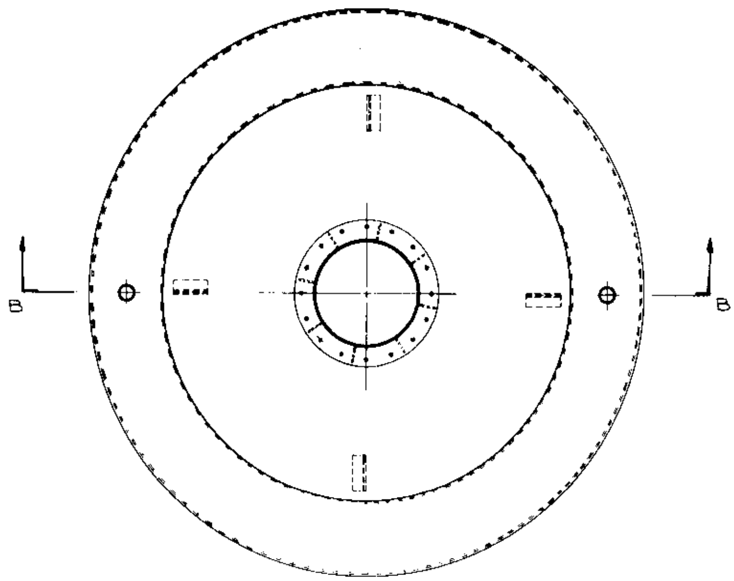
49. The preliminary design of a prototype processor has been developed to the extent of satisfying design goals and identifying fabrication problem areas. The proposed design is shown in detail in Figure 7 for 12-, 18-, and 24-in. pipeline systems. Geometric similitude is maintained over the size range shown so that all units display the proportions shown in the section BB view. The design incorporates a 15-deg conical diffuser section (E), a turning and radial diffuser section (F), and an impingement plate. The two diffuser sections fair together and are joined to form the diffuser assembly which is flange-mounted to the system pipe. The impingement plate is structurally supported by the diffuser assembly through an array of bolted struts.

50. Discharge Area Adjustment. The discharge area can be adjusted by changing the length of the support struts and in turn the height of the circumferential discharge opening, L. The recommended adjustment range for L is between one-half and one times the pipeline size. The lower limit is determined by the expansion profile through the processor. Above the upper limit, the flow will not fill the opening height, L. In Figure 7, the L dimension is shown at 5/6 times pipe size, which represents a good compromise between the expansion profile and radial flow conditions.

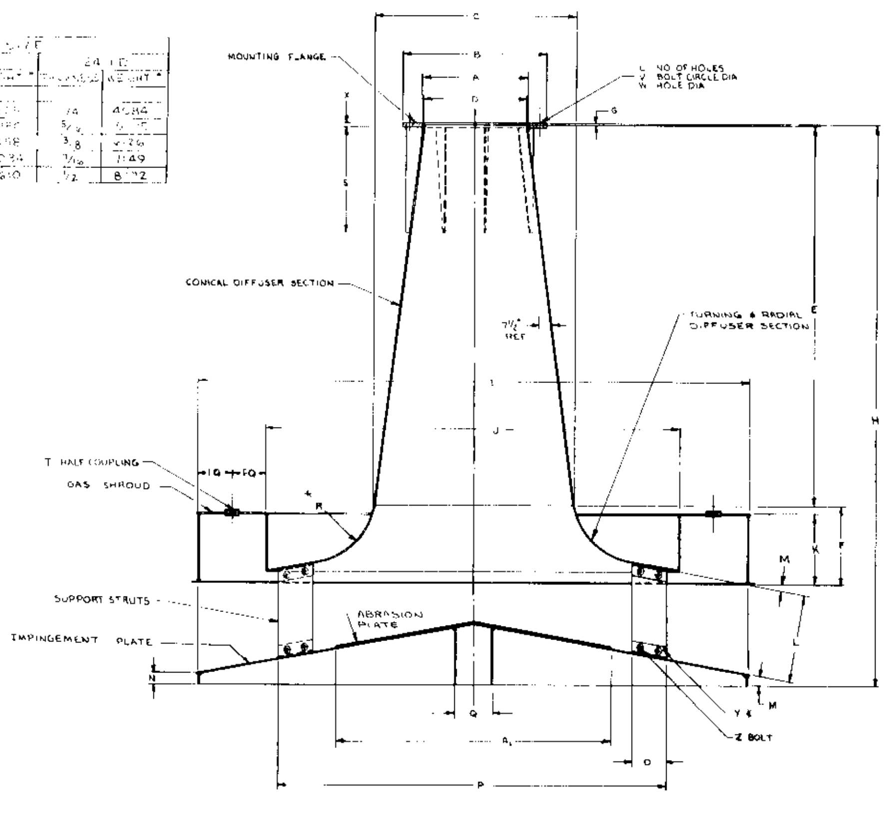
51. Stone and Debris Limits. The radial diffuser and impingement plate are parallel conical surfaces that slope down 10-deg (M, Fig. 7) from the horizontal. Stones and debris roll down the sloped surface and automatically clear the unit with the help of a small gravity component (0.17 g) and the drag exerted by the flowing slurry. The largest spherical object that can pass through the processor is determined by the height of the discharge opening, L, which can vary from one-half to one pipe diameter. For the setting shown in Figure 7 (5/6 times pipe size), the 18-in. processor can pass a 15-in.-diameter stone which is probably as much as the pipeline fittings (i.e., elbows, ball and socket joints) and centrifugal pump are able to pass. In the tangential direction, debris might have a tendency to hang up on or breech the struts. As shown in Figure 7, the spacing is approximately one pipe diameter for eight struts which is about the same as the maximum opening (L_{max}). In the final design, the number of struts will be limited to that required to satisfy the structural needs.

52. Abrasion Resistance. The impingement plate of the processor is subject to the most abrasion because it is exposed to the direct impact of the flow. The fact that the plate is in a region of the processor where the velocity is reduced to about one-quarter of that in the pipeline should relieve the problem somewhat, but nonetheless, an abrasion plate is used to protect the center portion of the impingement plate. The sizing of the support struts will include provision for high abrasion levels along their leading edges. Otherwise, the

DIMENSION	12"	18"	24"
A	12 5/16	18 3/8	24 3/8
B	19	25	32
C	23 5/8	35 5/8	46 7/8
D	12 3/16	18 1/4	24 5/16
E	43.4	65	86 1/8
F	9 5/16	13 15/16	18 7/16
G	7/32	9/32	9/32
H	64 7/16	96 7/16	127 3/4
I	64 1/8	96	127 1/4
J	48 1/16	72	95 7/16
K	8	12	15 7/8
L	10	15	19 7/8
M	10°	10°	10°
N	1 3/8	2	2 3/4
O	4	6	8
P	45 3/8	68	90 7/8
Q	4 1/2 (PIPE)	6 5/8 PIPE	8 5/8
R	8	12	15 7/8
S	12	18	24
T	1 1/2 NPT	2 NPT	2 1/2 NPT
U	12	16	20
V	17	22 3/4	29 1/2
W	1	1 1/4	1 3/8
X	11/16	3/4	1"
Y	1 1/2 × 1 1/2 × 1/4	2 × 2 × 3/8	2 1/2 × 2 1/2 × 1/2
Z	3/8 - 16	1/2 - 13	5/8 - 11
A_1	32"	48	64"



[illegible] PIPE SIZE					
12 I.D.		18 I.D.		24 I.D.	
THICKNESS	WEIGHT *	THICKNESS	WEIGHT *	THICKNESS	WEIGHT *
[illegible]	800				
1/4	[illegible]	1/4	[illegible]	1/4	4084
[illegible]	[illegible]	5/16	[illegible]	5/16	[illegible]
[illegible]	[illegible]	3/8	3458	3/8	[illegible]
		7/16	4034	7/16	7149
		1/2	4610	1/2	[illegible]



SECTION B-B

Figure 7. Full-scale diffuser processor design

wall thickness of the processor body shell will be sufficient to provide adequate abrasion resistance. A 5/16-in. thickness is used as the basis for the preliminary design estimates.

53. Sediment Gas Entrapment. The laboratory program revealed that turbidity is generated when entrained gas bubbles coated with sediment are released from the slurry. During the trip to the surface these bubbles shed some of the coating, and after the bubble reaches the surface and breaks, the remainder of the coating settles through the water column. Since entrained gas is commonly found in significant quantities in bottom sediment (5 to 30 percent by volume in upper Chesapeake Bay*), provision for its entrapment is incorporated in the processor design. This is implemented by an annular shroud, roughly square in cross section, that traps the gas bubbles as they rise out of the discharge slurry. The shroud is vented so that the trapped gas can escape to the atmosphere through hose lines that terminate above the water surface. Provisions for two of these vent systems are shown in Figure 7. In the final construction design an assessment of sediment gas flow rates will be used to determine the size and number of vent lines and to finalize the shape and dimensions of the shroud cross section.

54. Processor Specifications. The recommended full-scale processor is based on an 18-in. pipeline system. The specifications for the unit are outlined below (Figure 7):

---

*Verbal communication, Dr. M. Grant Gross, Director, Chesapeake Bay Institute, Johns Hopkins University, Baltimore, Md., April 1977.

Pipe ID	18 in.
Overall height	96-7/16 in.
Overall diameter	96 in.
Shell thickness	5/16 in.
Area ratio, $\frac{\text{Processor discharge area}}{\text{Pipeline area}}$	17.8
Flow rate, 20-fps pipeline velocity	4712 cyh
Discharge velocity	1.1 fps
Material	Steel
Dry weight	2880 lb

Fabrication Considerations

55. The processor should be a welded fabrication in sheet steel. Welding preparations and procedures should be in accordance with accepted practices for the dredging industry. The conical diffuser section can be formed by rolling and welding a template for the frustrum of a cone. The same template may be formed in halves or thirds by a succession of braking operations and the sections welded after forming. The mounting flange will be reinforced by a series of welded gussets since the processor is supported solely through this connection.

56. The turning section of the processor will be the most difficult section to fabricate because it is a surface of compound curvature. It can be hydraulically press-formed or spin-formed, both of which are quite expensive because of tooling costs. An acceptable hydrodynamic approximation of the compound curvature surface is the piecing together of identical tangential petals that are

curved only in the radial-axial plane and can be bent from flat stock. Since the welded petal assembly must interface with the conical diffuser section, the latter would be formed by the same technique and the transition from polygon to circular section would be located at the mounting flange. The gas shroud and the impingement plate can be fabricated with continuous curvature or by the tangential petal technique.

Barge Design

Functional Requirements

57. The role of the barge in the submerged discharge system is to provide support and handling capability for the processor. It must be easily coupled to the last section of pipeline and must serve as the pipeline anchor barge. It must be equipped with a derrick system that can raise, lower, and support the processor at a fixed elevation for long periods of time during dredging operations. The barge must also provide a platform on which the processor can be set while it is being adjusted and serviced or while the barge is being moved to a new location.

Design Details

58. The proposed design for the submerged discharge system is presented in Figure 8 for an 18-in. pipeline. A 45- by 20-ft barge provides sufficient space to accommodate the lifting system, appropriate

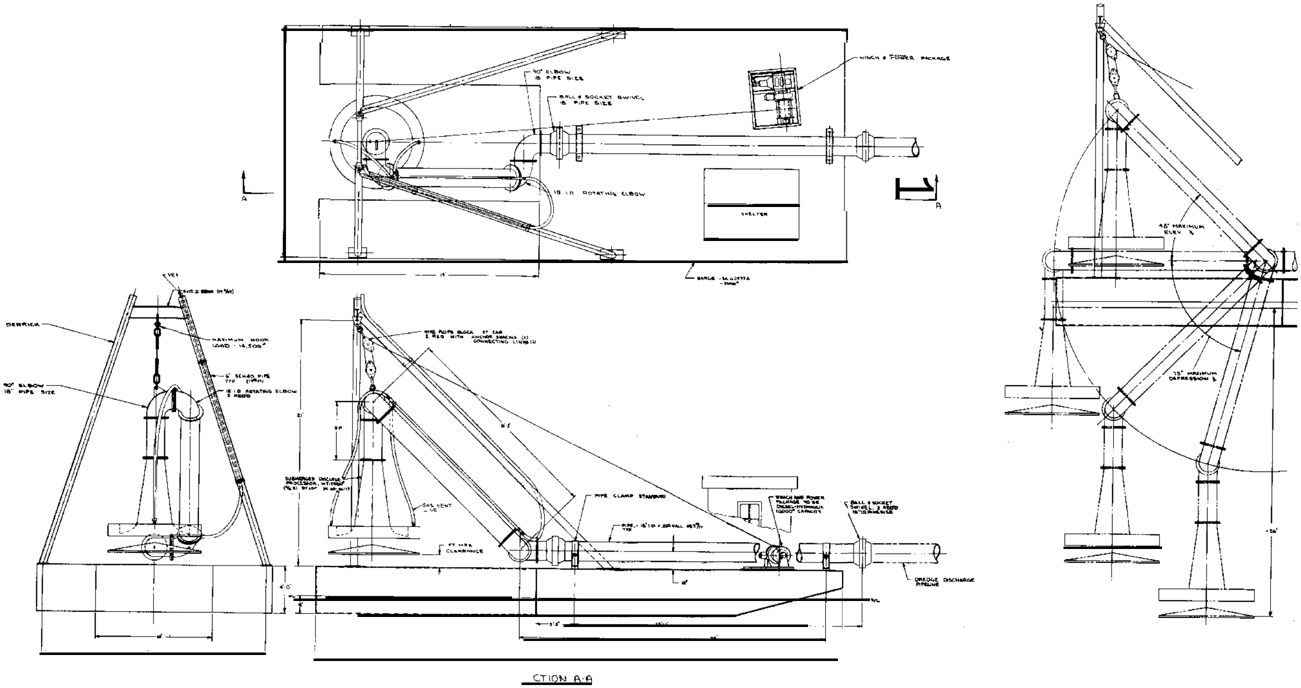


Figure 8. Submerged discharge system, full scale

piping, and the processor. The overall height of the system is 27 ft, the draft is 18 in., and the overall height above the waterline is 25.5 ft.

59. Pipeline System. The onboard pipeline is arranged along the centerline of the barge where it is secured by standard pipe clamps at a centerline height of 18 in. off the deck and 4 ft above the waterline. The pipeline system connects to the last section of pipeline by means of a standard 18-in. ball and socket swivel that accommodates singular misalignment between the discharge barge and the last pontoon float.

60. The most reliable pipeline arrangement for handling the processor and the pipeline is felt to be the pivot-boom system shown in Figure 8. The pivot boom is a section of pipe that is hinged at both ends and is installed between the rigid piping on the barge and the processor pipe section. By raising and lowering its free end, the pivoted pipe acts as a boom support for the processor and simultaneously carries the dredged slurry to the processor. The concept of a vertical hoist and flexible pipe (sand suction hose) was considered as an alternative method. However, it was rejected because the bend radius of the hose was too great to negotiate the necessary angular excursion and the reaction forces of the hose to vertical displacement of the processor were sufficiently large to move and tilt the processor so that at best the control over its positioning was poor.

61. The angular requirements for the pivots are set by the rotation of the boom section. At the full "up" position the processor

(bottom) is 1 ft above deck level and the boom is at a 45-deg elevation angle (Figure 8). At the full "down" position the processor (bottom) is 28.5 ft below deck level (26-ft draft) and the boom is at a depression angle of 75 deg. The total vertical travel is therefore 29.5 ft and the angular excursion of the boom and each pivot is 120 deg. These angles are far beyond the range of a ball and socket swivel (17 deg) or even a group of several swivels and can be accommodated only by a rotary joint. Each pivot is made up by mounting a standard 90-deg elbow to a 90-deg rotating elbow such that the rotary joint is between the two. As shown in Figure 8, the pivot assemblies cause the boom section to be offset from the piping centerline by two elbow radii of about 3 ft. The weight of the offset boom creates a moment and a shear force that must be supported by the rotating joint.

62. All of the components of the pipeline system are available in the dredging industry and should be assembled using methods and practices that are acceptable in the dredging field. A ball and socket fitting may be modified for rotary service; otherwise, the rotating elbow can be ordered as a special item.

63. Barge. The smallest barge that satisfies the needs of the submerged discharge system is 45 ft long by 20 ft wide by 4 ft deep. A barge of this configuration and size is readily available from manufacturers of small barges. The pipeline system is positioned on the deck (Figure 8) so that when the processor is in the full "up" position it is inside the envelope of the deck and can be lowered onto a deck cradle. This operation necessitates the 10- by 19-ft cutout

from the end of the deck so that the processor and boom section can move up and down without interference. The processor is supported on deck by two beams that span the cutout and rest on the pontoon decks.

64. The barge design emphasizes rugged construction because the vessel must withstand the rough conditions associated with normal dredging operations. A construction detail of the barge is shown in Figure 9. The hull is fabricated from 1/4-in. steel plate on sides and bottom and 3/8-in. plate on the deck. The internal structure consists of longitudinal and transverse bulkheads with reinforcing structure between. Foundations are provided for the four derrick legs and the six anchor bits. All internal surfaces are protected by an anticorrosion coating.

65. Derrick System. The derrick system consists of the support structures and the winch assembly (Figure 8). The derrick structure is a fixed A-frame that is supported by two diagonal legs and is positioned directly over the processor when the latter is at the full "up" position. The winch package consists of a hydraulically driven winch and a diesel engine power plant. The winch is rated for at least 10,000 lbs. The cable supports the load through a pair of cable blocks so that the maximum lifting capacity of the winch system is 20,000 lbs. The maximum anticipated hook load is 14,500 lbs so the system has a minimum margin of 38%. Winch features include variable speed control, direction control, hydraulic load holder circuit, and braking systems for normal operation, shutdown conditions, and for

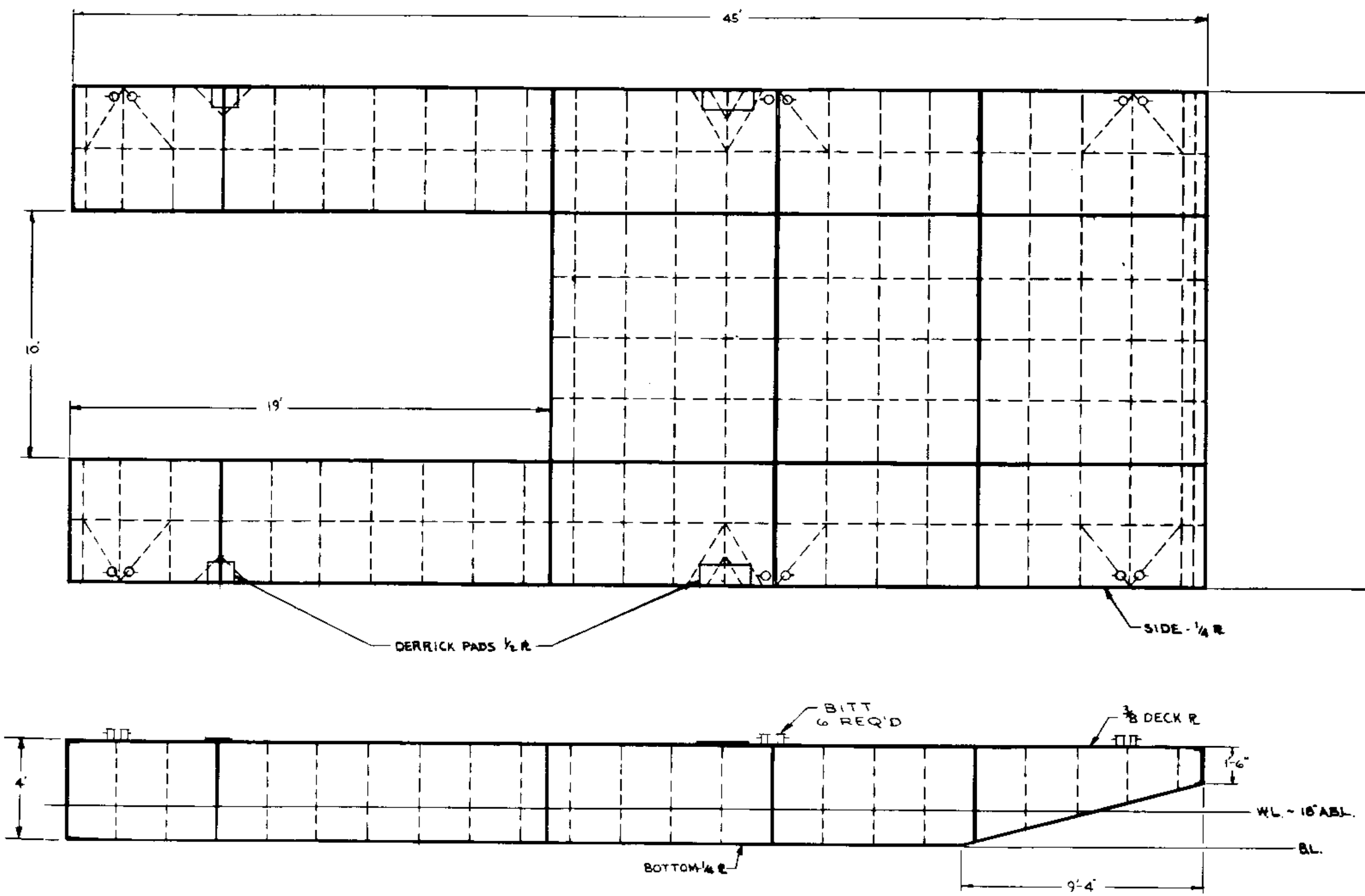


Figure 9. Submerged discharge barge, full scale

failsafe protection should all other braking systems fail to function. The winch package will include a self-contained fuel tank.

Barge Specifications

Pipeline size	- 18 in.
Barge length	- 45 ft
width	- 20 ft
height	- 4 ft
draft, loaded	- 18 in.
weight	- 35,000 lbs
Overall height	- 27 ft
Height above WL	- 25.5 ft
Lifting capacity	- 20,000 lbs
Maximum hook load	- 14,500 lbs
Lifting range	- 29.5 ft
Maximum processor draft	- 26 ft
Total system weight	- 50,000 lbs

System Operations

Dredging Cycle

66. The recommended operating procedures for the submerged discharge system are those for the ordinary discharge barge with the exception of certain adjustments that must be made to the processor. These can best be illustrated by reviewing the events in a normal dredging cycle. Presuming the submerged discharge barge is assembled

and in operating condition with the processor resting on its deck cradle and the pipeline is assembled on pontoons and in position, it is recommended that a work tug tow the barge out to the discharge end of the pipeline and hold the barge in position while the connection to the pipeline is made. The tug then should position anchors and secure the submerged discharge barge at the first discharge location. A sounding should then be made to determine the water depth. The first depth setting is determined by subtracting the desired height of the processor above bottom from the water depth. As an example, assume the sounding indicates a water depth of 16 ft, and it is desired to operate the processor 2 ft off the bottom. The processor should be lowered to a depth of 16 ft less 2 ft or 14 ft. The dredging operation should begin once the processor is set at its initial depth. As dredging continues, the settled slurry begins to mound in the immediate vicinity of the processor. After a period of time, the mound increases in diameter and height until it reaches the level of the bottom of the processor. Without interrupting the dredging operation, the processor should be raised another increment (2 ft in the example above) so that it does not become inundated by the mound and possibly plugged. The mound-building process continues as before except that with each successive equal vertical increment it takes a longer time for the mound to reach the bottom of the processor (because the incremental volume is increasing as the mound grows higher). The procedure is repeated as the mound continues to build toward the surface.

Mounding Characteristics

67. The principle of operation of the processor design causes the slurry to be discharged at low velocity without dilution so that the slurry tends to settle out quickly and mound in the immediate vicinity of the discharge point. As the mound builds under the processor, the critical shear slope is exceeded and the sediment probably moves radially outward until the slope is reduced to the critical value or less. The gross effect is that the height of the mounded sediment falls off linearly with distance from the processor so that the mound shape is approximately conical. In the absence of current, bottom slope, and terrain features, the mounding geometry appears as shown in Figure 10.

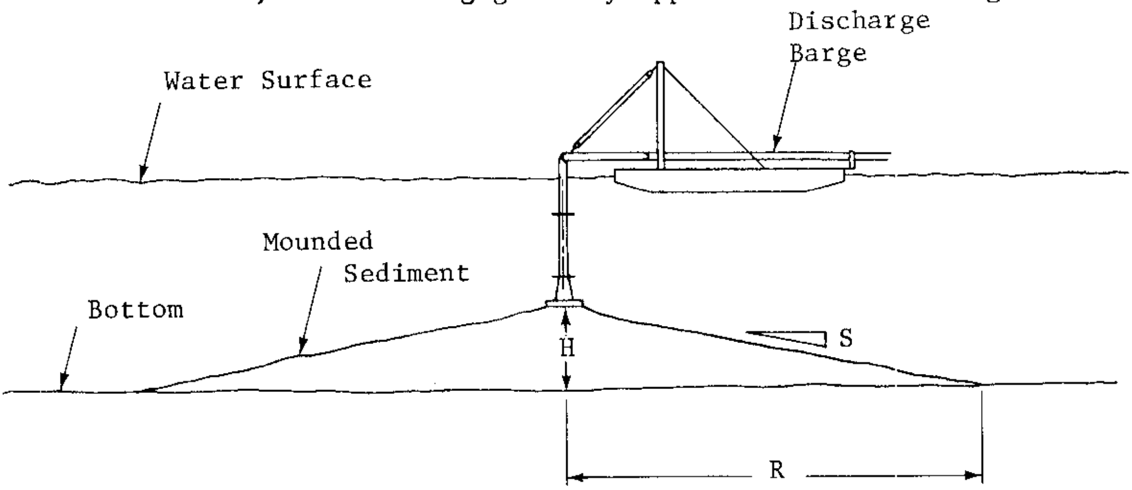


Figure 10. The conical mound

68. The dynamics of the mound formation can be modeled by equating the volume of solids in the mound with that pumped through the pipeline. That fraction of solids carried off in the water column and not deposited in the mound is assumed to be negligible. The volume of solids in the

mound is given by

$$V_{sm} = \frac{\pi}{3} R^2 H \beta_m \tag{5}$$

where:

V_{sm} = volume of solids in the mound

R = radius of the conical mound

H = height of the mound

β_m = solids ratio by volume, mound material

The volume of solids pumped is expressed by

$$V_{sp} = \frac{\pi}{4} D^2 V T \beta_p \tag{6}$$

where:

V_{sp} = volume of solids pumped

D = inside diameter of pipe

V = flow velocity in pipe

T = total dredging time

β_p = solids ratio by volume, pumped slurry

69. Since mound height, H, is of primary importance, R can be eliminated from equation (5) by the definition for slope, S.

$$S = \frac{H}{R} \tag{7}$$

Combining equations 5-7 gives the expression for the approximate total pumping time at one site, T.

$$T = \frac{1}{450} \quad \frac{H^3}{S^2 D^2 V} \quad \frac{\beta_m}{\beta_p} \tag{8}$$

The proper units for the terms in equation 8 are

T = days

H = ft

S = dimensionless

D = in.

V = fps

β = dimensionless

Since the solids ratio by volume is given by

$$\beta = \frac{1}{1 + \frac{\rho_s}{\rho_w}\left(\frac{1}{\alpha} - 1\right)}$$

where:

ρ = density

subscripts w = water

s = solids

$$\frac{\beta_m}{\beta_p} = \frac{1 + \frac{\rho_s}{\rho_w}\left(\frac{1}{\alpha_p} - 1\right)}{1 + \frac{\rho_s}{\rho_w}\left(\frac{1}{\alpha_m} - 1\right)} \qquad (9)$$

where:

α = solids ratio by weight

subscripts m = mound

p = pumped slurry

The final expression for dredging time is

$$T = \frac{1}{450} \times \left[\frac{1 + \frac{\rho_s}{\rho_w} \left(\frac{1}{\alpha_\rho} - 1 \right)}{1 + \frac{\rho_s}{\rho_w} \left(\frac{1}{\alpha_m} - 1 \right)} \right] \times \frac{H^3}{S^2 D^2 V} \tag{10}$$

70. The property values required in equation 10 were estimated from field measurements obtained by Nichols[6] around open water discharge operations in Mobile Bay and the James River. Although the slurry that discharged from the pipeline varied widely in density due to the movement of the cutter head, these variations averaged out to approximately 15 per cent solids by weight. Bottom samples indicated that the fluid mud mound contained approximately 25 percent solids by weight. Bathymetric data showed maximum bottom slopes in the range 1:200. Substituting the above values into equation 10 as well as a typical pipeline slurry velocity of 18 fps gives equation 11.

$$T = 8.834 \frac{H^3}{D^2} \tag{11}$$

71. A schedule of moves can be developed from equation 10 as a function of the fluid mud mound height. These data are presented in Table 1 at mound height increments of 2 ft. The recommended height of the diffuser above the bottom is specified so that at the end of a pumping period the diffuser is still one ft above the mound surface. The data of Table 1 indicate that (a) the adjustment schedule for the processor is reasonable in that it does not require frequent moves and

Table 1
Submerged Diffuser Adjustment Schedule

Time Period	Recommended Height of Diffuser Above Bottom At Beginning of Time Period, ft	Total Pumping Time (Days) Elapsed * At Disposal Site for Dredge Sizes						Mound Height (H) At End of Time Period, ft
		12-in.	16-in.	20-in.	24-in.	28-in.	32-in.	
1	3	0.5	0.3	0.2	0.1	<0.1	<0.1	2
2	5	3.9	2.2	1.4	1.0	0.7	0.6	4
3	7	13.2	7.4	4.8	3.3	2.4	1.9	6
4	9	31.4	17.7	11.3	7.8	5.8	4.4	8
5	11	61.3	34.5	22.1	15.3	11.3	8.6	10

* Elapsed times based on equation 10; ie. $\alpha_p = 0.15$, $\alpha_m = 0.25$, S = 1:200, $\rho_s = 2.66$ g/cc; $\rho_w = 1.01$ g/cc, V = 18 fps.

(b) the moving schedule for the submerged discharge barge will more likely be determined by dredge advancement than by capacity of the discharge location. In actual practice it is recommended that a moving schedule be developed for the specific discharge application and this schedule be used to make the necessary height adjustments at each location.

System Costs

72. Costs have been developed for an 18-in.-diameter submerged discharge system (Figure 8) consisting of processor (Figure 7) and barge (Figure 9) completely outfitted and ready for attachment to the end of the dredge pipeline.

Processor Cost

73. Processor cost includes labor costs and the construction cost of the hardware. The labor expense represents the engineering and drafting services required to design the first unit. The price of subsequent production units would be lowered considerably because

the labor expense is nonrecurring. The materials cost is based on the processor being completely fabricated by an outside vendor.

74. The cost for the first processor for an 18-in. discharge line is as follows:

Labor Cost	$20,648
Materials Cost	+ $12,938
First Unit Cost	$33,586

Barge Cost

75. The barge cost includes the basic barge fabrication (Figure 9) and the complete onboard structure, machinery, hardware, and pipeline required simply to connect the system to the end of the pipeline. Labor charges are for engineering and drafting service and for mechanical assembly. Follow-on barge systems would reflect a price reduction due to nonrecurring engineering and drafting charges. The materials cost for the barge systems includes the purchase of the hull from a small barge manufacturer. All pipe and fittings and winch machinery would be purchased from suppliers and installed by the prime contractor.

76. The cost for the first submerged discharge barge is as follows:

Labor Cost	$61,039
Materials Cost	+ $117,554
First Unit Cost	$178,593

Total System Cost

77. Total system cost is made up of the foregoing costs for processor and barge systems and breakdown in labor and materials categories as follows:

Category	Processor	Barge System	Total
Labor	$20,648	$61,039	$81,687
Materials	$12,938	$117,554	$130,492
Total	$33,586	$178,593	$212,179

Field Demonstration and Evaluation

78. The results of the scaled experiments and the system design study indicate that a submerged discharge diffuser would be effective in reducing turbidity and technically feasible to build and operate. Therefore, a field demonstration to evaluate a full-scale submerged discharge diffuser appears justified.

79. Ideally, a complete system, including the special barge with its equipment, should be built and tested in order to evaluate all aspects of the system. However, it may be feasible to adapt an existing barge and, as a first step, build and evaluate only the mechanical diffuser itself.

80. Regardless of the details of the approach, a demonstration and evaluation program would comprise certain principal tasks. These are described as follows.

Task 1: Evaluate Candidate Projects

81. In order to compile information necessary for the design of the discharge device and barge as well as for planning the project, existing or planned dredging projects that might be suitable for evaluating submerged discharge should be investigated, preferably by

visits to the sites. The purpose of these visits would be to obtain pertinent information about the dredge and its supporting equipment and about the project and its general vicinity.

82. The following are examples of information about the dredge that should be obtained:

- a. Dredge type and capacity.
- b. Size of discharge pipeline.
- c. Type of pipe and joints used.
- d. Pertinent characteristics of towboats used with dredge.
- e. Power available at discharge barge, if any.
- f. Support available on dredge (such as machine shop, welding, etc.).

83. The kinds of information required in connection with the project and its general vicinity include:

- a. Characteristics of disposal areas throughout the planned project. These would include water depth, bottom characteristics, salinity, and current and wave conditions.
- b. Characteristics of sediment to be dredged.
- c. Locations of accommodations.
- d. General availability of support, such as machine and welding shops, marine supplies, hardware, and miscellaneous gear.
- e. Availability of services for aerial photography.

Task 2: Prepare Detailed Designs

84. In this report, the design of the diffuser was carried to the point where it could be fabricated from the drawings available. However, before drawings can be released for fabrication, the system must be carefully integrated with the project selected for demonstration. Depending upon what types of pontoons or barges the particular dredge has, it may be that an existing piece of equipment could be modified for installation of the discharge device. However, it should be emphasized that the barge and discharge device comprise a system which, if it is to work properly, must have all parts carefully integrated.

85. Although the initial application would be a demonstration to verify the full-scale performance of this concept, the device should be designed for extended operations. The design should be rugged and materials should be selected to resist wear and to operate satisfactorily in a marine environment. In addition, the device should be outfitted to facilitate measurements and observations; such as provisions for sampling taps and possibly flow sensing.

Task 3: Construct the Diffuser System

86. Depending upon the location of the project selected for the demonstration and upon the Corps of Engineers' facilities, the discharge device might be built by a contractor while an existing barge is outfitted by the Corps. Another alternature would be for the Corps to contract for the entire system.

87. In any event, construction would be based on the design drawings developed in Task 2, and should be of a quality that is consistent with the best grade of hardware that is generally considered good practice in the dredging industry.

Task 4: Conduct Field Evaluation

88. Field evaluation would consist of monitoring the initial dredging operations (no diffuser) for a period of 3 to 5 days. It should include aerial photography to record the extent and nature of the observable discharge plume.

89. Water samples should be taken and transmissometer measurements made, if possible, to establish the degree and extent of turbidity in the water column both near the discharge point and downstream in the plume. Samples should be taken near the bottom in order to determine whether or not a mud flow is being generated.

90. If the water depth allows, stakes should be placed to serve as references to determine the amount and extent of mounding, if any, in the vicinity of the point of discharge. In order to characterize the slurry being discharged, samples should be withdrawn periodically from the pipeline near the discharge.

91. The following specific subtasks would comprise this phase of the demonstration:

- a. Make necessary visits to coordinate effort and to arrange for all support services required.
- b. Prepared the field test plan.

c. Conduct all monitoring and field operations.

d. Analyze samples and reduce data.

e. Prepare final report.

Schedule

92. The recommended field demonstration and evaluation would require approximately seven months to complete. The estimated time would be one month each for Tasks 1 and 2, two months for Task 3 and three months for Task 4. The total time required would be seven months.

CHAPTER IV: BASELINE TEST PROGRAM

Purpose and Scope

93. The selection of the diffuser described in the last chapter was based primarily on a laboratory test program of four designs relative to a baseline condition. The baseline test program was designed to explore the physical characteristics of the fluid mud and turbidity systems that typically develop around those open-water discharge configurations that are in common use in hydraulic dredging operations. Inasmuch as the program was a laboratory effort, the discharge configurations had to be scaled down to a size that could be conveniently tested in a laboratory facility. The performance data from this program constitutes the reference base against which the performance of each processor design was compared and evaluated. These data were also used as the source data upon which the predictive correlations were established. In this section the open-water discharge pipe configurations are described, the system parameters are outlined, scaling considerations are discussed, the laboratory test facilities and procedures are described, and the results and conclusions of the baseline program are presented and discussed. The processor testing program is discussed in Chapter V.

Test Plan

94. The objective of the laboratory test program was to assess the performance of several typical open-water discharge configurations, both above-surface and submerged, at one representative operating condition and then to establish the performance characteristics of the most commonly used configuration over a range of operating conditions. The evaluation was made in terms of readily measurable properties of the turbidity and fluid mud systems within the physical limitations of the laboratory test facility.

Submerged Discharge Configurations

95. In order to benefit from past experience where submerged discharge had been used in the field, JBF Scientific Corp. conducted a nationwide survey of Corps of Engineers district offices and dredging contractors. The notes on the survey are included in Appendix A. A total of 20 contacts were made including 16 district offices and 4 contractors. Of these, nine (eight districts, one contractor) had no experience with submerged discharge and three had used the techniques but had kept no records of these applications. Of the remaining eight users, half were handling coarse sandy material and the rest were handling fine-grained material. The sand dredging operations utilized submerged discharge in some cases as a means of improving the placement accuracy of material on the bottom and in other cases as a means of providing more accurate mounding control particularly where minimum water depths were prescribed. The submerged discharge was used in maintenance dredging

operations either to reduce surface turbidity or to place the discharge material more accurately on the bottom in trench backfilling applications. Of those that documented their experience, half reported a noticeable reduction in surface turbidity with the use of submerged discharge (as compared with above-surface discharge). The other half reported no improvement in surface turbidity with the use of submerged discharge. The latter group was composed primarily of those engaged in sand dredging operations, where the material was coarse, and relatively free of the fine-grained material that generally causes turbidity plumes.

96. The submerged discharge configurations that were used in the reported operations included bleeder pipes, a baffle or deflector plate on the end of the pipe, and the simple pipe termination without attachments. The bleeder pipe was slotted over a considerable length to promote dispersion of a sandy, turbid mixture over an extended bottom area and to simultaneously reduce surface turbidity. The design did not reduce turbidity significantly, and it still created mounding problems; consequently, its use was curtailed. The baffle or deflector plate on the end of the submerged pipe served as an impingement plate that dispersed the dredged material over a wide bottom area in order to reduce mounding at the impact point. This design was used by Williams-McWilliams Co. with dredged material ranging from coarse sand to clays. They reported a reduction in apparent surface turbidity with its use.

97. The most commonly used termination was the simple pipe without attachments, probably because it could be lowered into the water to

the desired depth without significant modifications to the discharge system. An elbow and straight extension could be added to orient the discharge pipe vertically downward. Atkinson Dredging Co. reported the use of a vertical submerged discharge for very coarse dredged material (sand and shell) with an attendant reduction in surface turbidity.

98. JBF Scientific Corp. performed a study around a cutterhead dredge operating in Mobile Bay ship channel during the summer of 1976. The submerged discharge configuration was a single pipe termination that was implemented by lowering the last length of discharge pipe into the water to the angular limit of the last ball and socket fitting. The discharge pipe rested at a depression angle of approximately 20 deg from horizontal so that the end of the pipe was 4 ft below the surface in 12-ft of water. JBF personnel had the opportunity of witnessing an above-surface discharge and a submerged discharge under identical operating conditions of the dredge system (including dredged material), and concluded that the submerged discharge generated less surface turbidity than did the above-surface discharge.

99. On the strength of the survey results and JBF experience, the selection of discharge configurations included the following:

- a. Horizontal pipe, above surface
- b. Horizontal pipe with baffle plate, above surface
- c. Horizontal pipe, submerged
- d. 20-deg pipe, submerged
- e. Vertical pipe, submerged

The horizontal above-surface pipe with deflector plate was included to show the effects of dispersing the dredged material before it hit the water surface.

100. The test plan was arranged so that each of these five configurations was tested under identical operating conditions, thus enabling a direct comparison of the performance of each at that single condition. The remainder of the program was directed toward the testing of the most commonly used submerged configuration over a range of operating conditions. On the basis of the survey results, the 20-deg submerged pipe was selected as the most commonly used configuration.

Scaling Considerations

101. In order to use the results of laboratory tests to predict the behavior of full-scale mud flows, a knowledge of the scaling laws is necessary. The fluid mud system generated by an open-water discharge follows the basic laws of a gravity flow in which kinetic energy terms and potential energy terms are directly related. The relationship is expressed conventionally in terms of the Froude number which represents the ratio of intertia forces to gravity forces and is given below in terms of fluid mud parameters

$$F = \frac{V}{\sqrt{g' h}} \tag{12}$$

where V is the forward velocity of the head wave, g' is the apparent acceleration of gravity, and h is the height of the head wave. The value for g' is given by the net buoyancy of the denser layer relative to the less dense medium by:

$$g' = \left(\frac{\rho_m - \rho}{\rho}\right) g = \left(\frac{\Delta\rho}{\rho}\right) g$$

The density of the fluid mud is given by ρ_m and that of the surrounding water by ρ. With the gravity term corrected for buoyancy, equation 12 is referred to as the densimetric Froude number. The expression for head wave velocity is obtained directly from equation 12 for the steady-state case where the Froude number is constant.

$$V = \bar{F}\sqrt{\left(\frac{\Delta\rho}{\rho}\right) gh} \qquad (13)$$

102. The scaling procedures that were used in the laboratory program generally followed the recommendations of Middleton for the small-scale modeling of fluid mud flows.[5] These procedures are listed and discussed below.

- a. Froude numbers were kept constant for model and prototype (i.e., full-scale).
- b. Reynolds numbers for the head wave were always in the turbulent regime ($Re \geq 1000$)

Froude number reflects the fundamental behavior of the gravity-driven flow, dictates some of the second-order effects, and establishes the relationship between head wave velocity, mud layer thickness, and density difference of the turbidity system according to equation 13. The moving sediment wave interacts with the water column and generates friction forces between the fluid mud flow and the bottom surface. A similar friction force is created at the upper interface between the sediment wave and the upper water column.

103. The friction condition at the bottom interface is the same as that for open channel and pipe flow. For fully developed turbulent flow of the fluid mud wave the friction factor becomes virtually independent of Reynolds number and is determined solely by the relative bottom roughness (ratio of roughness amplitude to fluid mud wave height). The Reynolds number of the head wave is

$$Re = \frac{Vh}{\nu} \tag{14}$$

where ν is the kinematic viscosity of the fluid mud. In the laboratory test program, head wave Reynolds numbers fell in the turbulent regime, and the bottom friction factor was insensitive to Reynolds number for the bottom roughness ratio of the test tank (approximately 1:50). In other words, from test to test and from model to prototype, the bottom friction factor was constant. Friction conditions at the upper interface are governed primarily by Froude number with little or no influence exerted by Reynolds number. Friction factor at the upper interface is established solely by Froude number and therefore is directly scalable from model to prototype system.

104. The mixing conditions that exist at the upper interface determine the amount of sediment that is transported into the upper water column to form a turbidity cloud. Since turbidity control is a major objective of the program, turbidity and the process of its generation must be correctly represented and scaled. According to Middleton[5], the mixing process at the upper interface is a function of the Froude number so that at high values the mixing is vigorous, whereas at low values little or no mixing takes place. Since the threshhold between the two regimes occurs at a Froude number of 1.0, the role of Reynolds number in the mixing process is at best a minor one. In the laboratory program the mixing process and the generated turbidity were scaled between model and prototype systems according to Froude number. Natural sediment was used in the test program to preserve the physical properties of the sediment (i.e., kinematic viscosity, flocculation properties) and to simplify the preparation of the test slurry.

105. The scaling rationale can be summarized as follows:

- a. Constant Froude number for model and and prototype systems establishes
  - (1) Scaling of the basic fluid mud system.
  - (2) Scaled mixing with the water column.
  - (3) Scaled friction at the upper interface.
- b. Turbulent fluid mud layer establishes scaled friction at the bottom interface.

106. The mechanics of Froude number scaling are derived from equation 12, which is repeated below.

$$F = \frac{V}{\sqrt{g'h}} \tag{12}$$

If the Froude number is constant and g' is the same in model and prototype systems, then

$$\frac{V_p}{V_m} = \sqrt{\frac{h_p}{h_m}}$$

where subscripts p and m refer to prototype and model, respectively. If the ratio of dimensions is defined as the geometrical scale factors, then

$$s = \frac{h_p}{h_m} \tag{15}$$

and

$$\frac{V_p}{V_m} = \sqrt{s} \tag{16}$$

Substitution of $V = \ell/t$, where ℓ is the general length dimension and t is time, in equation 16 gives

$$\frac{\ell_p}{\ell_m} \times \frac{t_m}{t_p} = \sqrt{s}$$

and

$$\frac{t_p}{t_m} = \sqrt{s} \tag{17}$$

Equations 15-17 give the following:

a. Length scale = s

b. Velocity scale = $\sqrt{s}$

c. Time scale = $\sqrt{s}$

107. The scaling rationale for the discharge configuration can be illustrated in the case of the horizontal above-surface discharge as shown in Figure 11.

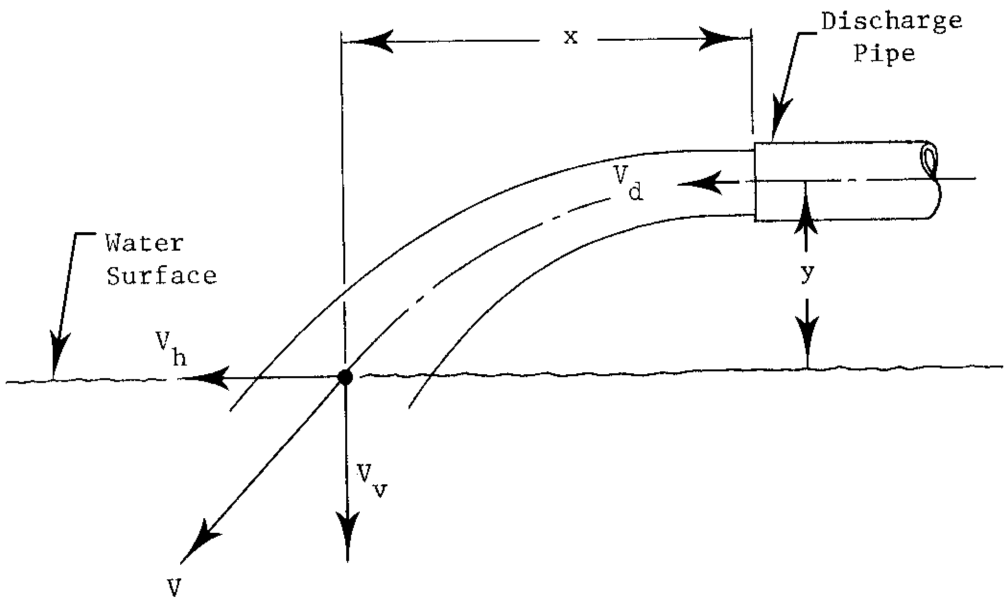


Figure 11. Schematic of horizontal above-surface discharge

Figure 11 shows that the angle of the jet as it enters the water surface must be maintained from prototype to model. This simply means that the ratio of velocity components, V_h/V_v, must be constant. The ratio can be expressed as

$$\frac{V_h}{V_v} = \frac{V_h}{\sqrt{2gy}}$$

Since V_h is equal to the pipe discharge velocity, V_d,

$$\frac{V_h}{V_v} = \frac{1}{\sqrt{2}} \frac{V_d}{\sqrt{gy}} \tag{18}$$

Geometric similitude can be expressed by the ratio x/y as follows:

$$\frac{x}{y} = 2\left(\frac{V_h}{V_v}\right) = \sqrt{2}\left(\frac{V_d}{\sqrt{gy}}\right) \tag{19}$$

Equations 18 and 19 are both functions of the discharge Froude number, F_d, where,

$$F_d = \frac{V_d}{\sqrt{gy}} \tag{20}$$

Equations 18 and 19 express the fact that Froude number scaling of the pipe discharge velocity, V_d, and the height of the pipe above the water surface, y, will guarantee geometric similitude between model and prototype.

The gravity term in equation 20 is the earth's acceleration for the above-surface discharge since this is the effective acceleration acting to deflect the discharge jet. Since the pipe discharge velocity and discharge dimensions must be scaled by Froude number to maintain geometrical and dynamical similitude, the scaling relationships for slurry flow rate is derived from the equation

$$Q = V_d\left(\frac{\pi}{4}\right) d^2$$

Since discharge velocity, V_d, scales as $s^{1/2}$ and discharge pipe diameter, d, scales as s, volume flow rate scales as $s^{5/2}$.

108. The scaling rationale for the submerged discharge configuration is more complicated but basically similar to that developed for the above-surface case.

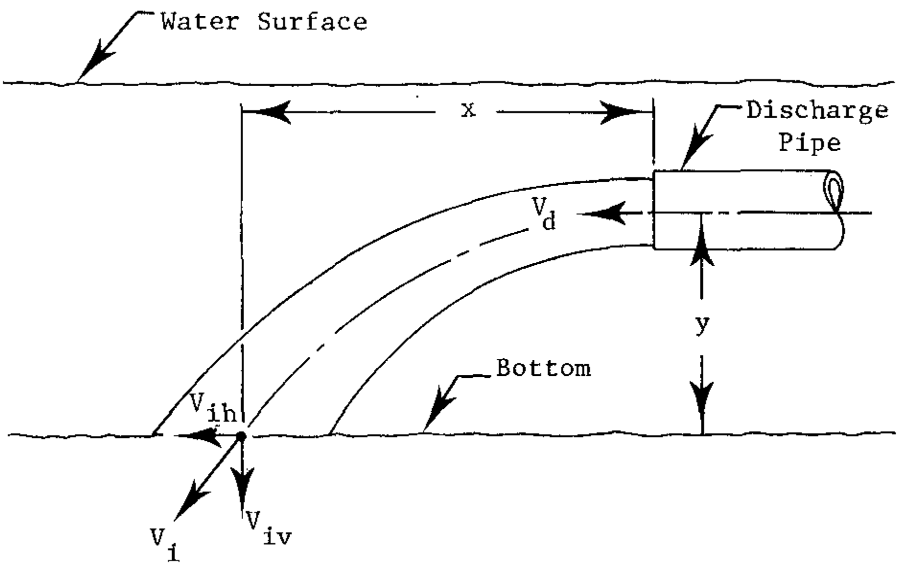


Figure 12. Schematic of horizontal submerged discharge

Figure 12 shows schematically the horizontal submerged discharge jet system. Upon discharging into the water column, the jet immediately comes under the influence of the apparent gravity field (due to the difference in densities of dredged material and surrounding water) and begins to curve down toward the bottom. The jet also starts to entrain water which causes its velocity and density to decrease. Along the jet centerline then, the apparent gravity force becomes weaker and the vertical velocity of the jet decreases. Since the primary force acting on the system is gravity, in the conversion of potential energy to kinetic energy it is reasonable to expect that similitude would be maintained by Froude scaling where the Froude number is given by

$$F = \frac{V_d}{\sqrt{g'y}}$$

$$g' = \left[\frac{(\rho_d - \rho)}{\rho}\right] g = \left(\frac{\Delta\rho}{\rho}\right) g \qquad (21)$$

where: ρ_d = density of dredged material

y = height of discharge above bottom

109. The results of the scaling considerations can be summarized as follows:

a. Froude number scaling will be used throughout the fluid mud system.

b. Actual sediment will be used in all model tests.

c. All linear dimensions will scale according to the factor s.

d. All velocity will scale as $\sqrt{s}$.

e. Time will scale as $\sqrt{s}$.

110. As an example of how the scaling laws are applied, consider the procedure that was used to size components in the test model. A full-scale system was specified in terms of typical average conditions that might be encountered in the field. These were as follows:

Dredge pipe inside diameter	20 in.
Flow velocity in pipe	18 fps
Water depth	20 ft
Height of submerged pipe above bottom	10 ft (middepth)
Volume flow rate	17,600 gpm

Practical limitations of the test tank system suggested a scale factor of about 20 to 1. This determined the test model specifications as follows:

$$\text{Pipe inside diameter} = 20 \times \frac{1}{20} = 1 \text{ in.}$$

$$\text{Flow velocity in pipe} = 18 \times \frac{1}{\sqrt{20}} = 4.0 \text{ fps}$$

$$\text{Water depth} = 20 \times \frac{1}{20} = 1 \text{ ft}$$

$$\text{Height of pipe above bottom} = 10 \times \frac{1}{20} = 0.5 \text{ ft}$$

$$\text{Volume flow rate} = 17{,}600 \times \frac{1}{(20)^{2.5}} = 9.8 \text{ gpm}$$

Test Matrix

111. The test program was designed to evaluate the influence of several independent system variables on the geometry and behavior of

the fluid mud layer. In order to accomplish this with a reasonable number of tests, each variable was assessed individually with respect to a standard reference or baseline condition that was determined by considering average or typical conditions that exist in the field, reducing these conditions down to model scale, and establishing the requirements for the tank facility, particularly the mud deployment system. The reference configuration was specified as follows:

Discharge configuration	Submerged pipe
Pipe ID	1.049 in. ID
Pipe depression angle	20 deg
Discharge height above bottom	1 ft
Discharge velocity	4 fps
Discharge flow rate	11 gpm
Dredged material	
source	Boston Harbor
type	Saltwater clayey silt
Discharge solids ratio	23 percent solids by weight
Bottom type	Smooth (wood)
Water	
type	Fresh
depth	2 ft

The 20-deg submerged pipe configuration was selected from JBF field experience and the survey of users; the above pipe size and flow rate were commensurate with the available mud supply and pump delivery capability. The water depth was set at 2 ft rather than the 1 ft that represented the scaled field water depth (20 ft) to prevent the water surface from interfering with the fluid mud cloud especially for those tests that tended to increase cloud height (i.e., higher discharge flow rate and greater discharge height above bottom). The discharge height above bottom was set at middepth in anticipation of the need to test above and below this position. Boston Harbor mud was used because its properties were satisfactory and it could be obtained readily in sample-size volumes. The solids content of 23 pcs (percent solids by weight) was higher than the 20 pcs planned because of difficulties associated with the measuring and monitoring procedures. The smooth, hard tank bottom was taken as the standard because its roughness was stable and repeatable, and it was free of the maintenance, repair, and large additional mud supply required for a sediment bottom. Fresh water was selected because the expense of salt water, in terms of time and money, could not be justified.

112. Of the foregoing list of system variables, most were treated as independent variables and their influence was established by testing a limited number of values of each variable usually on either side of the baseline value. Each variable was tested only with respect to the baseline conditions; i.e., all other variables were held at baseline values. The matrix of tests is presented in Table 2 in terms of the values around the baseline configuration. The two above-surface tests were run at the baseline conditions except where their geometries created differences. These two tests are outlined individually in the table.

Table 2

Test Matrix for the Baseline Program

Water Type	Sediment Type	Sediment Concentration	Bottom Type	Discharge Pipe Size, ips in.	Discharge Angle deg	Discharge Velocity fps	Discharge Height Above Bottom in.	
				Submerged				
Salt	Silty Clay	16	Sediment	3/4	Horizontal	2	6	
Fresh	Clayey Silt	23	Smooth	1	20 Submerged Discharge	4	12	Reference Conditions
Salt Layer	Silty Sand	30		1-1/4	Vertical	6	18	
				Above-Surface				
Fresh	Clayey Silt	23	Smooth	1	Horizontal	4	30	(6 in. above Surface)
Fresh	Clayey Silt	23	Smooth	1 with Baffle	Horizontal	4	30	(6 in. above Surface)

113. Fresh water was used as the standard water type because it was the most readily available. The saltwater test was intended to demonstrate the influence of salinity on head wave dynamics and on flocculation and settling. The saltwater condition was implemented by salting fresh water to a salinity of 30 $^{\circ}/_{\circ\circ}$. The salt layer was intended to simulate a freshwater discharge area that had been penetrated by a saltwater wedge. The layer was 8 in. thick, at a salinity of 30 $^{\circ}/_{\circ\circ}$, and was established by slowly introducing salt water along the bottom of the tank after it had been filled with fresh water.

114. The Boston Harbor mud that was used as the standard sediment consisted of about 15 percent sand, 55% silt, 30 percent clay, and was classed as a clayey silt. The grain size distribution and organic content are shown in Figure 13. The clay (Table 2) represented a finer grained sediment and was obtained by fortifying the Boston Harbor mud with kaolin clay to increase the clay content to about 50 percent. The silty sand (Table 2) was formulated by adding enough sand to the Boston Harbor mud to raise the sand content to about 50 percent.

115. The sediment concentration was approximately 23 pcs for the baseline condition, 30 pcs for the high density condition, and 16 pcs for the low density test. The 30-pcs concentration represented the practical delivery limit of the mud supply system, and the 16-pcs condition represented an equal concentration increment in the direction of lower density.

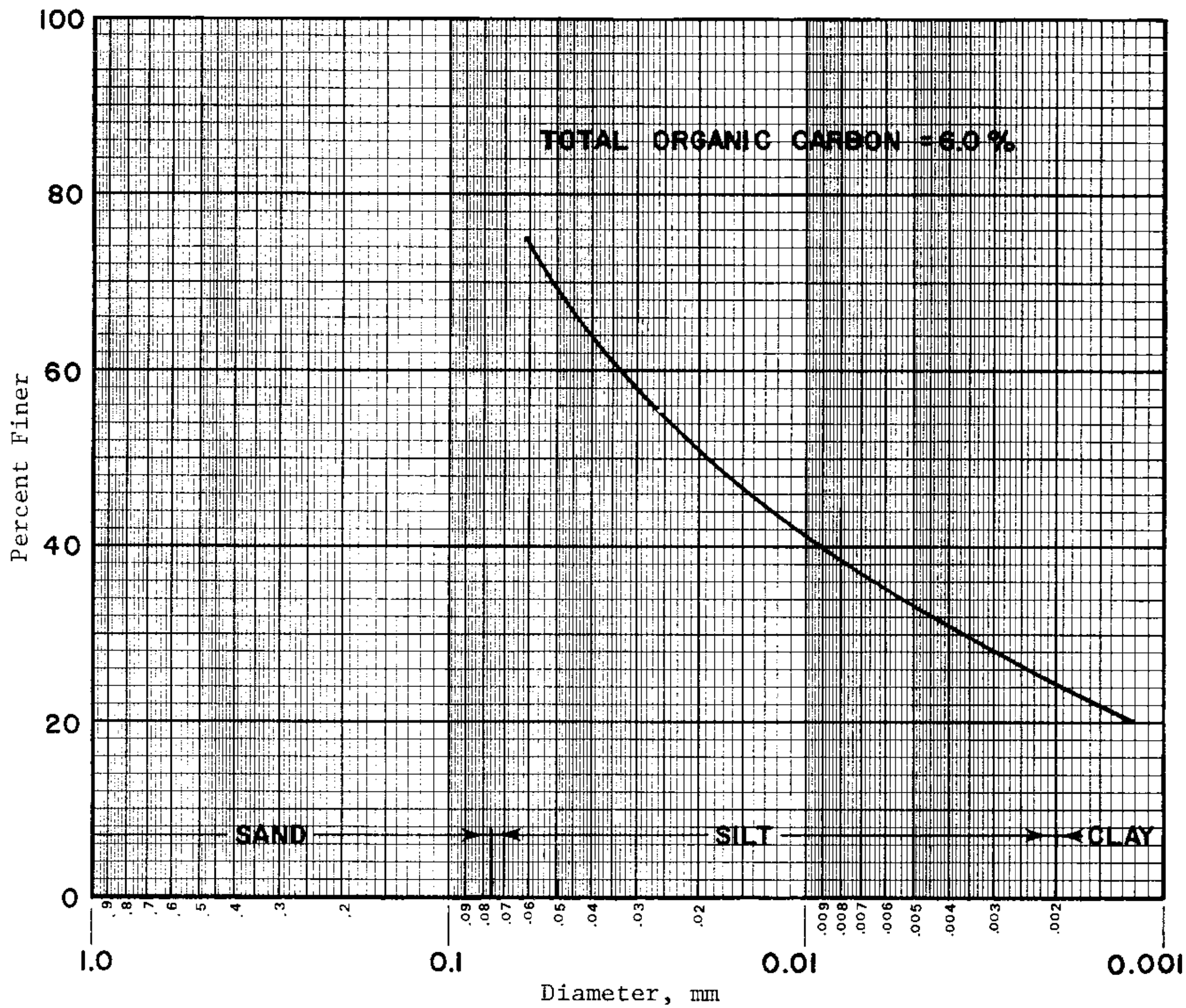


Figure 13. Grain size distribution for Boston Harbor sediment

116. A compatible bottom was selected for comparison with the smooth bottom used for the baseline condition. The compatible bottom was formed by trowelling down a 1-in.-thick covering of mud on the bottom of the tank. Grab samples of Boston Harbor mud with a concentration of approximately 35 pcs was used. The texture of the compatible bottom surface was relatively smooth although it was characterized by a pattern of trowel marks.

117. The variables relating to the pipe discharge were set according to the capabilities of the test facility. The discharge pipe size was varied one iron pipe size (ips) above and below the 1-in. size (1.049 in. ID) used for the baseline runs. The 1-1/4-in. ips (1.380 in. ID) approached the flow limit of the mud supply system, and its flow rate exceeded the baseline flow rate (11 gpm) by about the same factor as the 3/4-in. ips (0.824 in. ID) flow rate was below the baseline value. The horizontal and vertical discharge pipe orientations were tested in addition to the submerged discharge angle of 20° because they represent configurations that have been used in the field. The discharge velocites were selected at 6 fps and 2 fps around the baseline value of 4 fps. The higher value was close to the flow limit of the mud supply system, and the lower velocity represented the lower limit of stable mud flow that could be maintained. The discharge heights above the bottom were chosen at 6" above and below the middepth location of 1 ft. (baseline) in order to cover a reasonably wide range of the total water depth and

to simulate a discharge that was located closer to the surface (18 in. off bottom), as well as one that was closer to the bottom (6 in. off bottom).

Test Facilities

Test Tank

118. The test tank was constructed of wood and equipped with plexiglass observation windows on both sides. Figure 14 shows the tank, which was divided into two sections by a movable partition. Each section was approximately 4 ft wide, 2 ft deep, and 32 ft long. Two tests were run for each filling of the tank. The viewing windows were used in conjunction with vertical scales placed at 4-ft intervals along the tank's longitudinal centerline for observation and photography. Color-coded bars at 1-in. intervals on the scales aided in reading the cloud height during the tests and in the photographs. Figure 15 shows the scales in position for a test and Figure 16 shows a closeup of the mud flow as it passes one of the scales.

119. To facilitate filling and cleaning, both ends of the tank were provided with a drainage trough and plumbing cross-connection. The troughs extended almost the full width of the tank and prevented localized turbulence during filling or emptying. The plumbing arrangement permitted adjustment and balancing of the flow on either side of the partition during filling and emptying. This was particularly important during

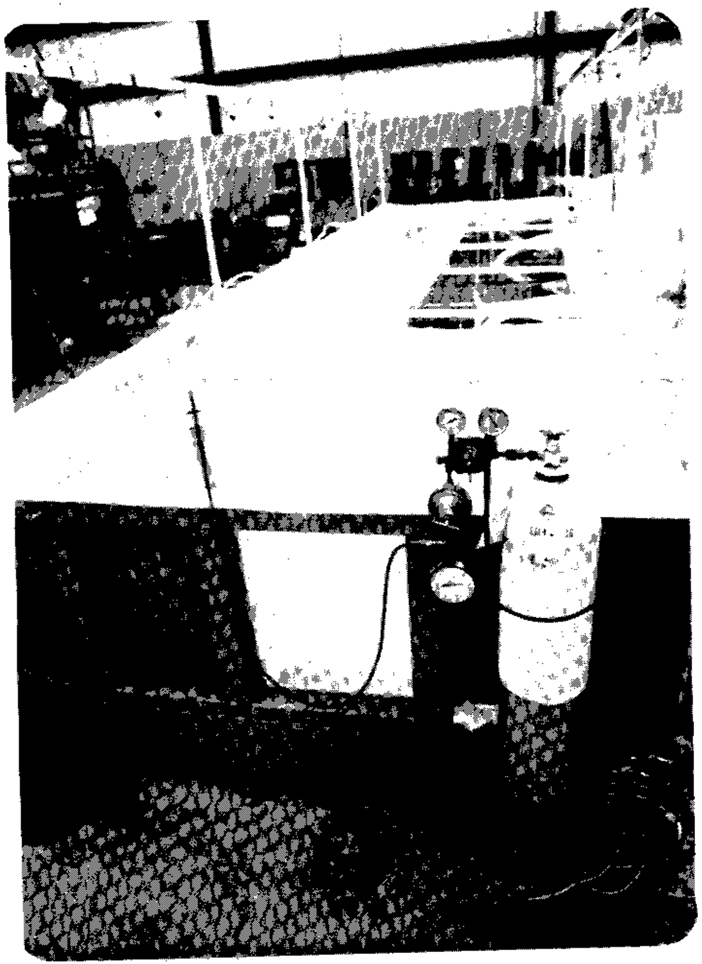


Figure 14. Test tank

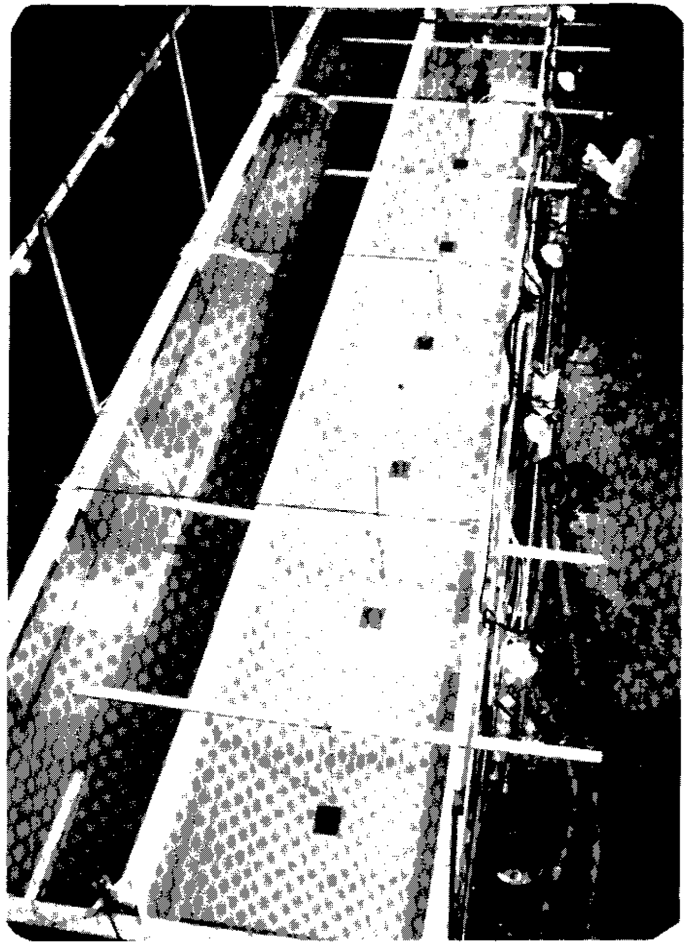


Figure 15. Test tank with vertical scales in position

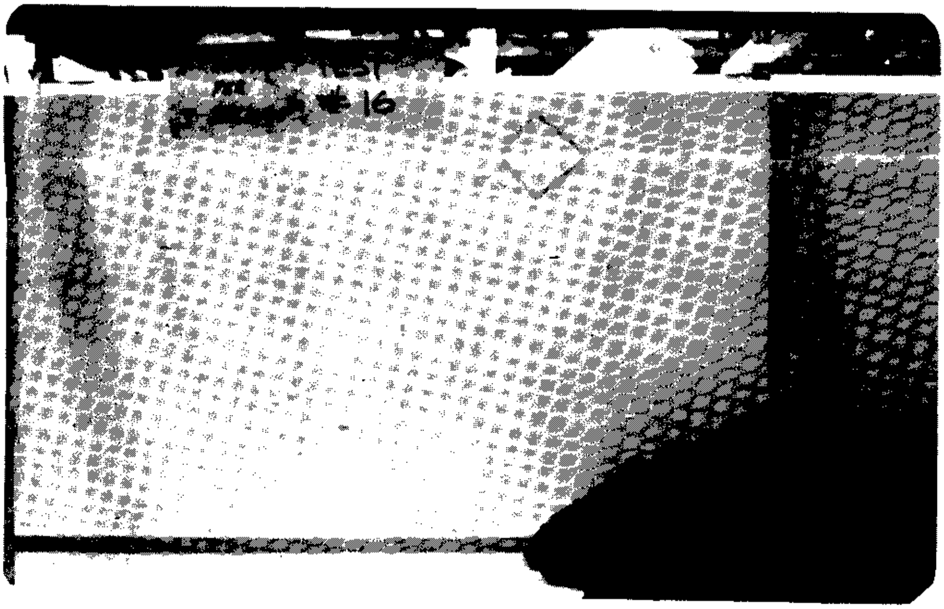


Figure 16. Typical head wave passing vertical scale

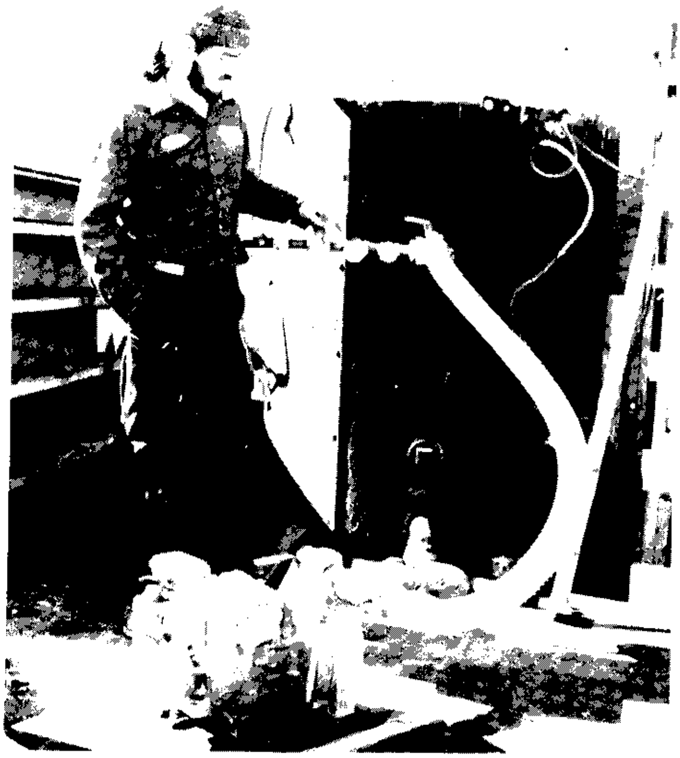


Figure 17. Slurry storage and conditioning tank

emptying to prevent disturbance to the sediment deposited on the tank bottom after a test.

Slurry Storage and Conditioning

120. A 400-gal tank and a recirculating pump were used to hold and deliver slurry at a calibrated rate (Figure 17). Usually 350 gal of slurry were prepared and added to the storage tank. The slurry was mixed to get the solids into suspension; then they were kept in suspension by recirculation. During a test, some of the recirculated slurry was diverted to the test tank, as shown in Figure 18. The pressure gauge was used in conjunction with the valves to maintain a constant flow rate to the test tank. Seven or eight tests were run from a single filling of the storage tank.

Water Supply

121. Water used in the tests had to be of high clarity for effective photography. The available tap water contained excessive amounts of suspended solids which colored the water and restricted visibility. To meet the required clarity levels water for the tests was obtained from a 40,000-gal pool of treated water. Treatment included low-level chlorination to destroy organics, flocculation of suspended solids, and filtration through diatomaceous earth. Pumps were used to transfer processed water to the test tank and for partial emptying of the tank while final emptying was done by gravity.

Mud Flow Sampling

122. Mud flow sampling called for simultaneous collection of samples at seven different depths, each at three different locations. To handle

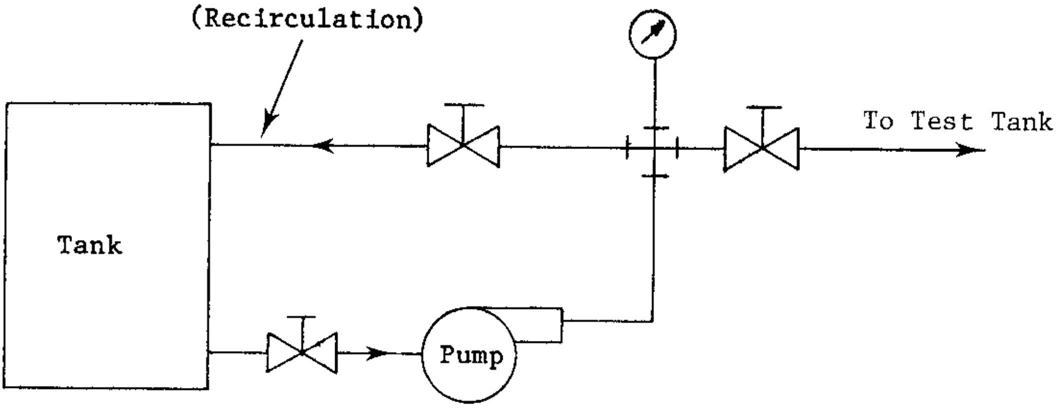


Figure 18. Plumbing and valving schematic for recirculation/delivery

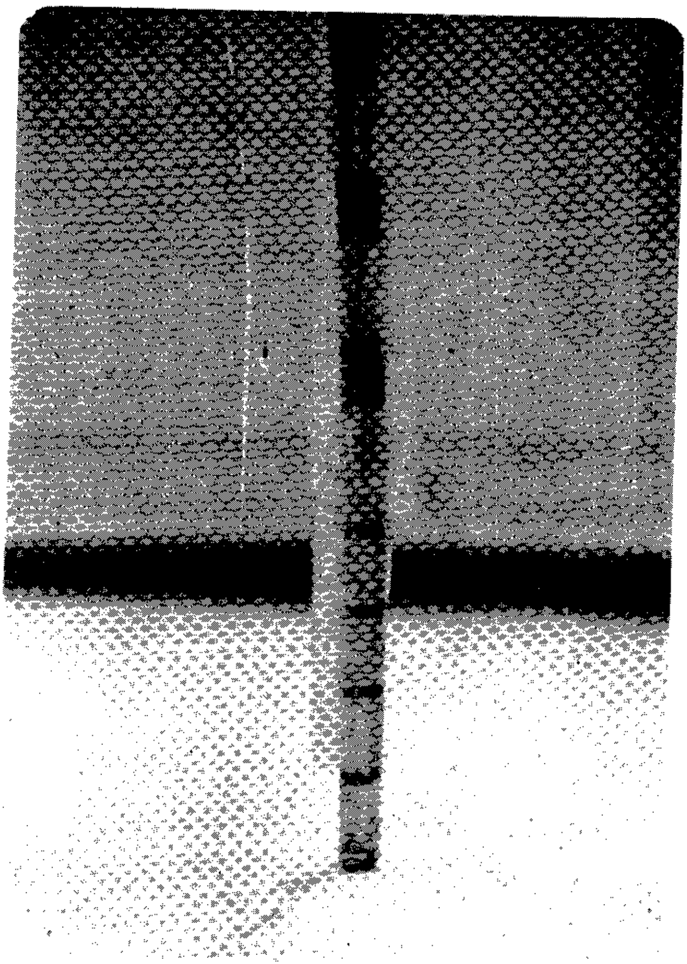


Figure 19. Sampling probe

21 simultaneous samples, a siphon sampling system was designed. At each sampling station, the sampling devices consisted of a probe (Figure 19) with tube ends fixed at 1, 2, 3, 4, 6, 8, and 10 in. above the tank bottom. The tubes were 0.25 in. in diameter and extended back over the tank wall to a valving and collecting system (Figure 20). The siphons were primed and valved off prior to each test. At the appropriate time, the three banks of samplers were purged and the samples were collected.

123. The mud flow sampling system was designed to obtain representative samples with minimum interference with the flow. The probe was small and posed little or no obstruction to the mud flow. The 4 fps sampling velocity in the tubes was enough to carry the suspended solids without causing excessive turbulence at the sampling point. The devices were reliable, and 21 samples could be collected simultaneously.

Sediment Sampling

124. Bottom sediment samples were obtained by using an open-ended tray that sat on the bottom as shown in Figure 21. It was positioned with the open ends perpendicular to the flow so that it presented no impediment to the flow. Because of the open ends, the tank had to be emptied slowly and the trays removed carefully.

Photographic Equipment

125. Lighting for the photography was provided by a bank of photoflood lamps above the tank. Two 35mm still cameras and two super 8 movie cameras were used during each test. The movie cameras were used for continuous overhead coverage and side cinematography and one

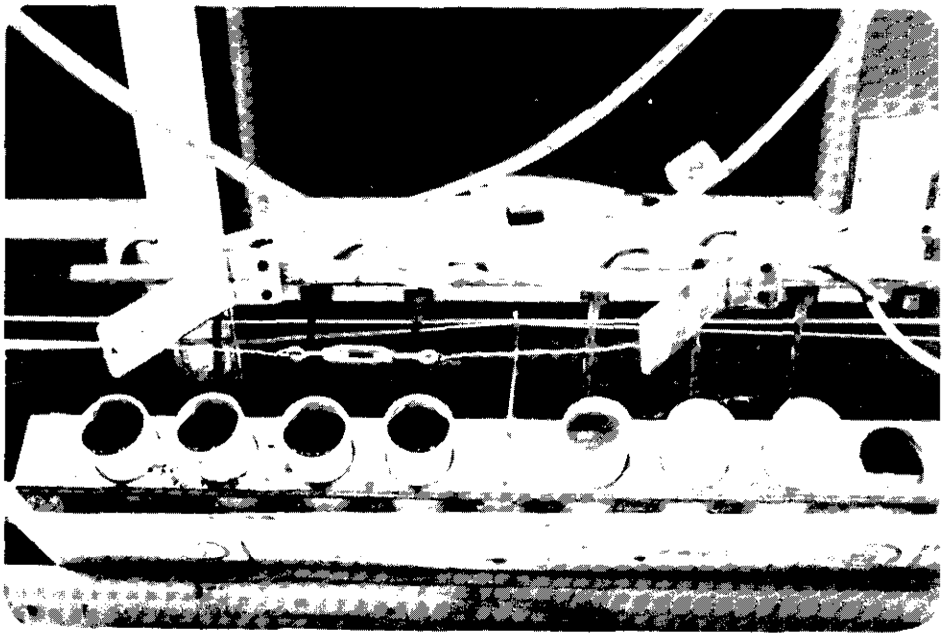


Figure 20. Water sample collecting system

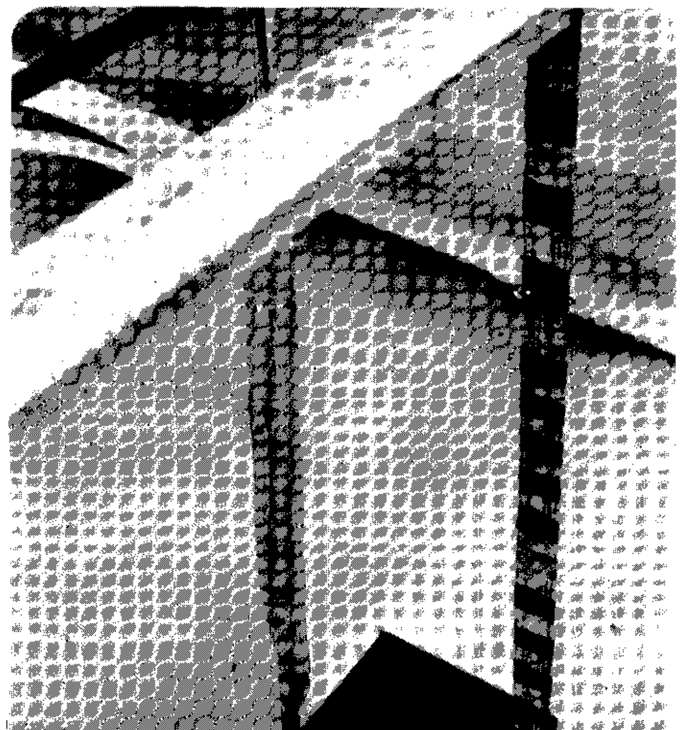


Figure 21. Bottom sediment sampling tray

still camera were used to photograph the mud flow as it passed the vertical scales. The second still camera, which was used to photograph the discharge area, was motor driven and actuated by an electronic timing control. Figures 22a and b show the motorized 35 mm camera and the timing control in place for a test run.

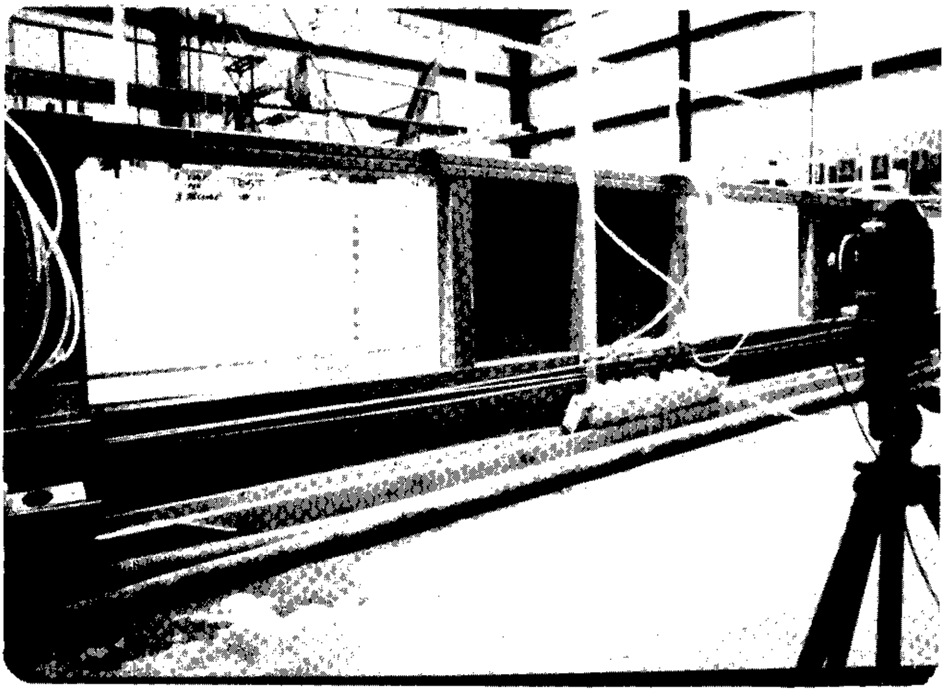
Timing

126. Timing of the mud flows was done in three ways: (a) continuous motion pictures were taken, (b) observers with stopwatches noted the times as the mud flow passed the vertical scales, and (c) pictures were taken with a clock in the field of view. The cinematography provided the greatest accuracy. The number of frames shot per second was calculated from the movie camera time calibration data. The frame count between test events was used to find the times, and stopwatch times were used for backup.

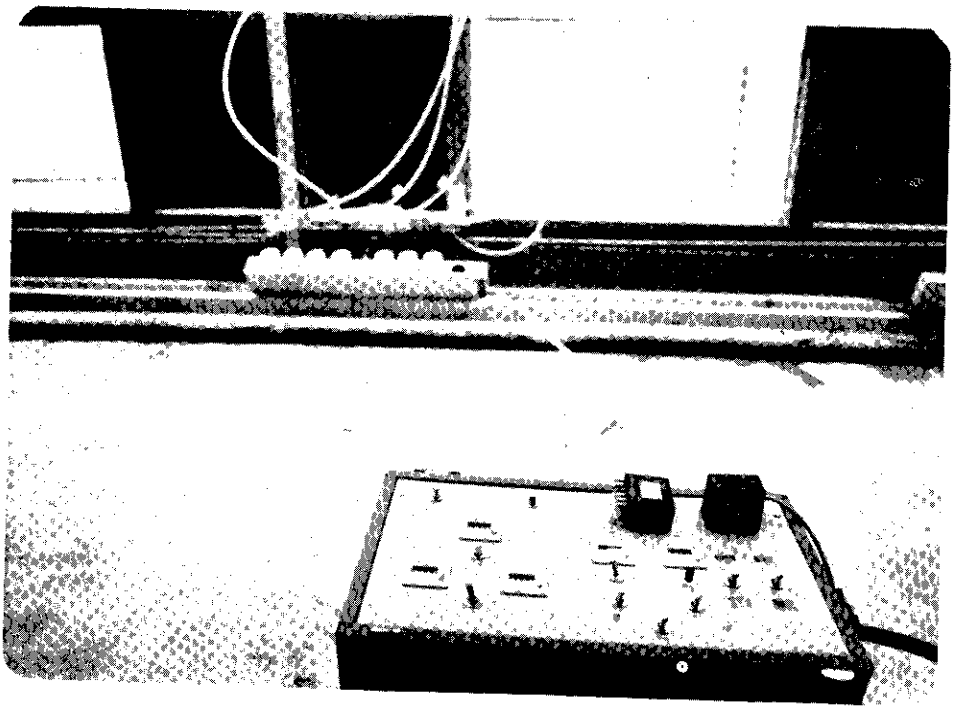
Test Methods and Procedures

Typical Test Operation

127. To prepare the sediment slurry, drums of sediment were weighed and sampled for solids content. The sediment was then transferred to a mixing vessel, coarse debris was removed, and sufficient freshwater was added to obtain the desired solids concentration. The slurry was strained through 1/4-in. wire mesh and transferred to the slurry storage system. Three or four hours before a test, the slurry was thoroughly mixed and the recirculation pump started.



a. Motorized camera in position



b. Camera timing control

Figure 22. Motorized camera and timing control

128. Approximately 4000 gal of processed water were used for each filling of the tank. Transferring the water from the treatment pool took between 30 min and an hour. During this time, the sampling devices, the vertical scales, and the test identification numbers were put in position. For accuracy and consistency during the program, the location of each sampler and vertical scale was marked on the tank. The test identification labels were placed so that they would appear in all the photographs. When the tank was full, the siphons on the water samplers were primed and valved off.

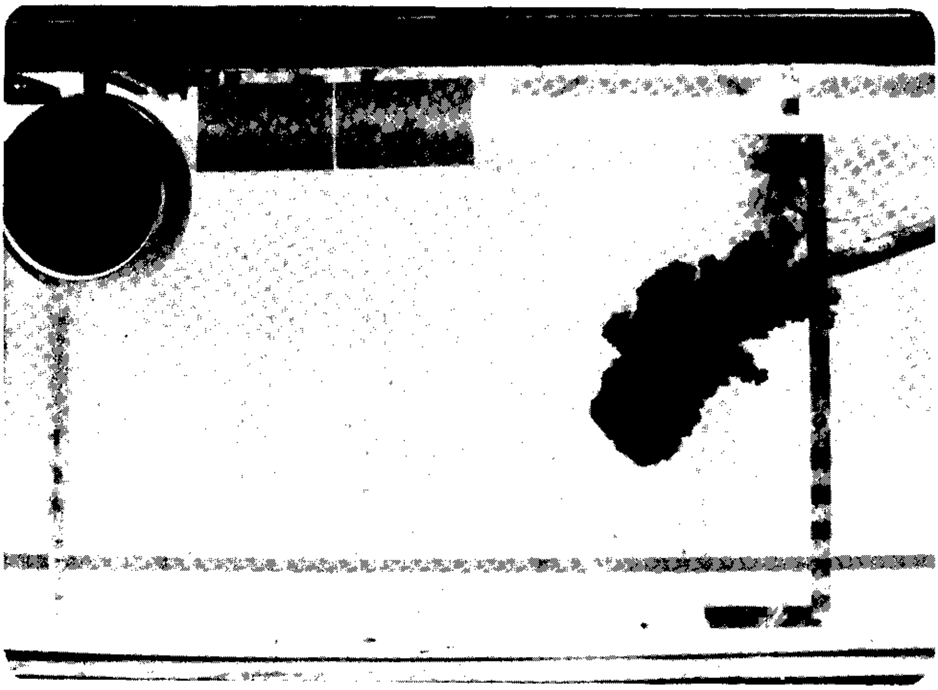
129. The slurry delivery system was calibrated just before each test. The slurry was mixed thoroughly and the pump started 3 to 4 hours before the anticipated test time. The flow rate was checked by timing the filling of a calibrated drum using the delivery hose. If any adjustment in the flow was required, the necessary valve adjustments were made. This calibration was continued until the desired flow rate, usually 10 gpm, was obtained. A sample of the slurry pumped during the calibration was taken for laboratory verification of the solids content.

130. Final preparations for a test included checking the lighting, positioning the cameras and the discharge device. During each test, both motion picture and still photographs were taken. Each test lasted 2 to 4 min, and since the distance covered by the mud flow in that time was 28 ft, personnel could make only cursory observations. The movies and slides provided a permanent record from which information on the dimensions of the mud flow, differences and similarities between the tests, and motion of the mud flow could be obtained.

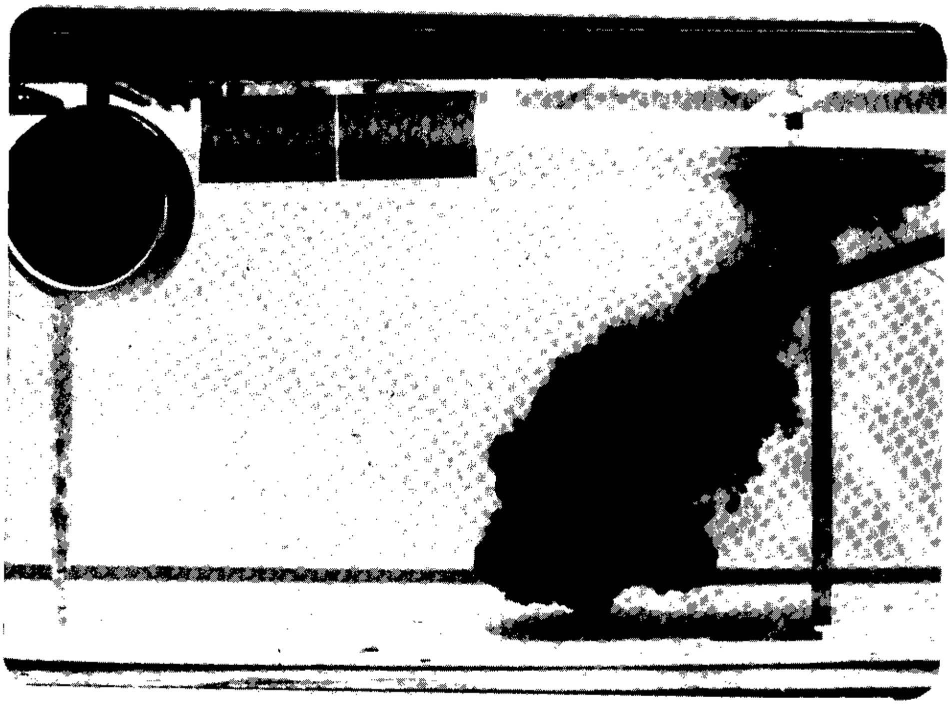
131. A Nikon R10 Super 8 movie camera was used for overhead photography. The cameraman, who was positioned about 15 ft above the tank opposite the starting point, filmed the entire test without interruption. This provided a continuous record of the head wave itself and the time at which it passed each vertical scale. Concurrent with the overhead photography, a second cameraman took continuous side movies with a Nikon R8 Super 8 camera. These films provided a permanent record of the profile characteristics of the mud flow.

132. At the point of discharge, a motorized 35mm Nikormat was used to take slides every second at the start of a test and then every 30 sec thereafter. These slides recorded the profile of the jet, its impact with the bottom, and the discharge area once the mud flow had propagated down the tank. Figures 23a-d show the beginning of a typical test run. A clock mounted in the field of view provided real time. As time and opportunity permitted, a fourth cameraman took 35mm slides of the test, concentrating on general aspects and getting profile shots of the mud flow and the head wave as they passed vertical scales.

133. During the test, two observers timed the mud flow with stop-watches. They noted the times that the mud flow passed each vertical scale and made observations about the cloud height. When the mud flow reached the 24-ft point in the tank, the water samplers were actuated, purged of tank water, and released to collect samples (Figure 24). While the tank was draining, the mud flow samples were transferred to storage bottles. As the tank level dropped and the mud cloud cleared,

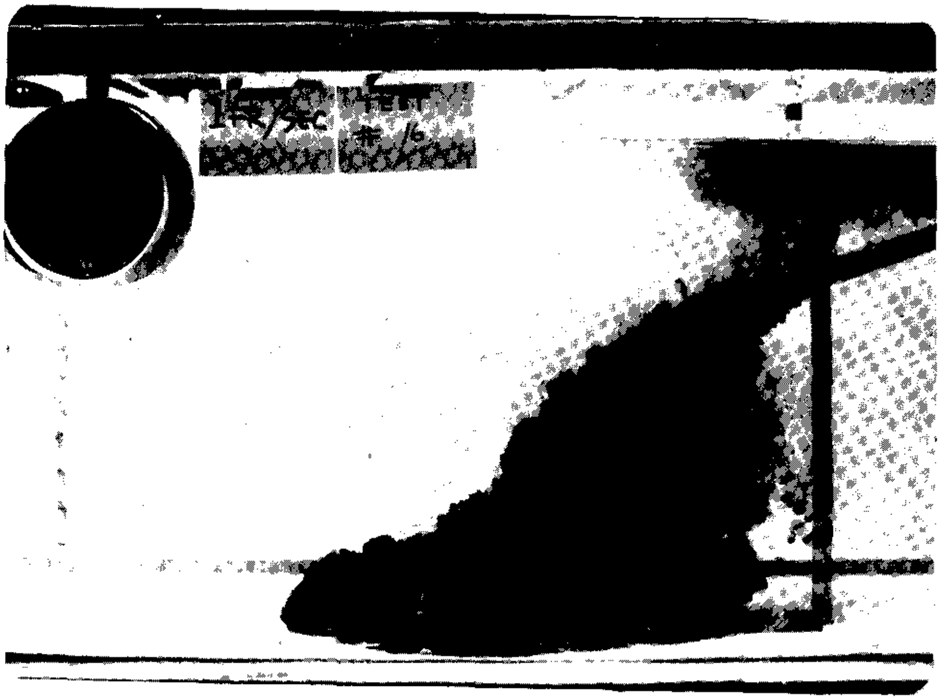


a. Discharge jet, time 0 sec.

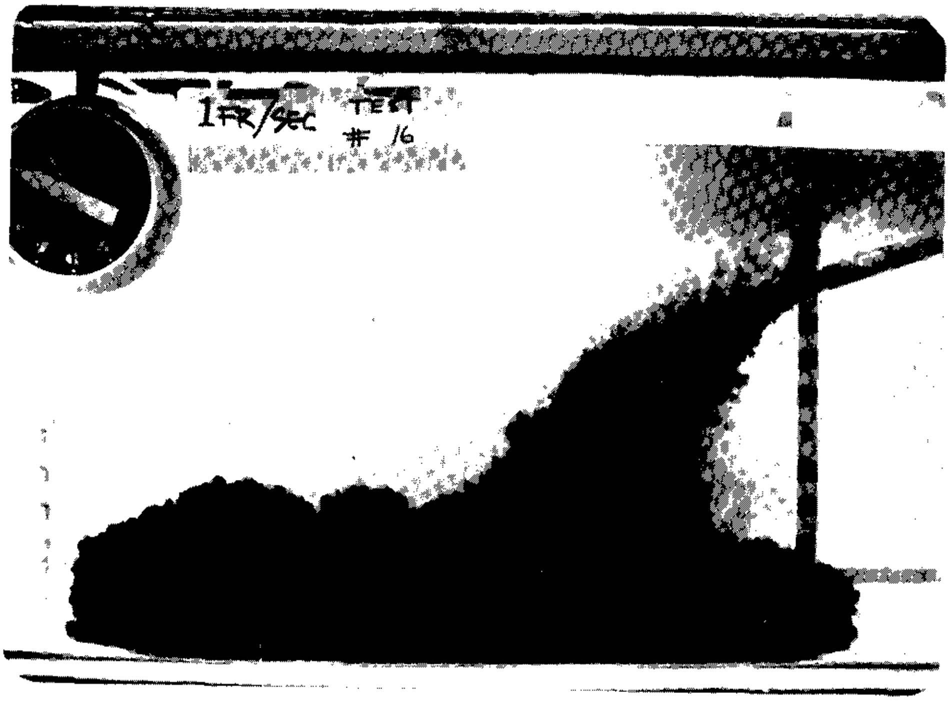


b. Discharge jet, time 2 sec.

Figure 23. Typical test run



c. Discharge jet, time 4 sec.



d. Discharge jet, time 7 sec.

Figure 23. Typical test run (continued)

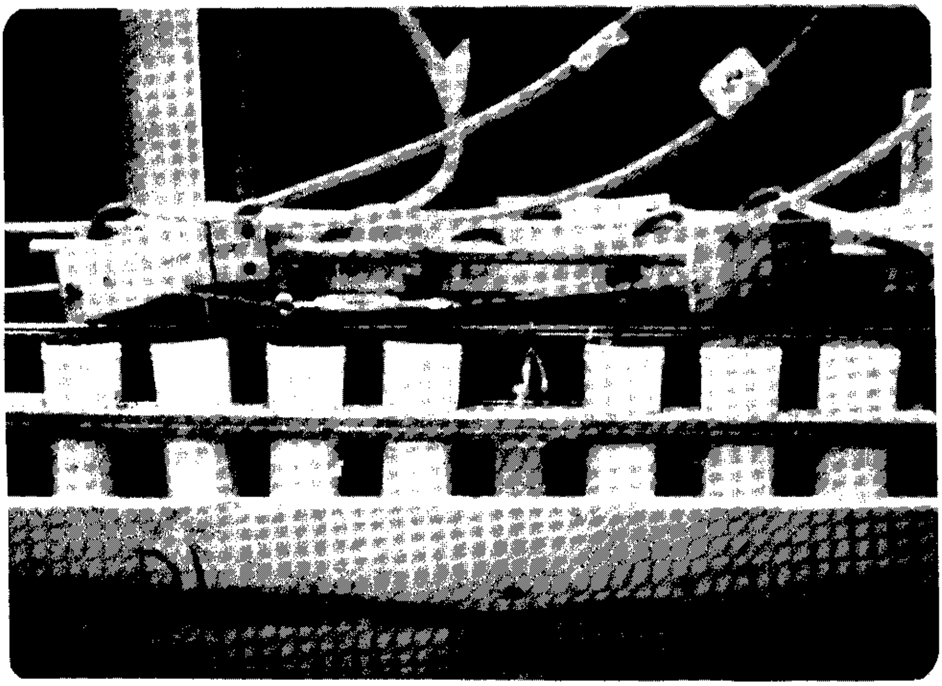


Figure 24. Water samples being collected

measurements were made of the thickness of the sediment deposited around the discharge device. When the bottom samplers were visible, they were removed and the sediment washed into storage bottles.

134. The last step in a test run was cleaning the tank, which was done immediately to keep the sediment from drying on the tank. The sediment was flushed into the troughs, pumped out, and the tank was washed down to remove all traces of sediment.

Sample Processing

135. Slurry samples were analyzed for solids content. Each sample was thoroughly agitated and approximately 20 cc weighed in a drying dish of known weight. After drying at 106°C to constant weight, the dish was weighed again. Analyses were performed in duplicate and the percent solids calculated as the average value. The formula used was:

$$\frac{\text{wt. of solids}}{\text{wt. of liquid + solids}} \times 100 = \%\ \text{solids by weight}$$

136. Mud flow samples were analyzed for suspended solids gravimetrically. The volumes of samples used ranged from 5 mℓ to 200 mℓ depending on the apparent solids content. The samples were dried to a constant weight at 106°C. The suspended solids content was expressed in milligrams per litre.

137. Bottom samples were analyzed for solids content. Because these samples were collected by washing, an unknown volume of water

had been added. The sample was allowed to settle and the clear supernatant decanted. The sediment was then transferred to a drying dish of known weight. Settling was permitted again and the clear supernatant decanted. The samples were dried at 106°C to a constant weight. The solids content was expressed in milligrams of settled sediment per square centimetre of the sampling tray.

Test Results

138. A total of 32 tests were performed in the tank to complete the baseline program. The first 10 runs were conducted primarily to develop techniques for performing the tests and to adjust or calibrate test equipment and instrumentation. In addition, the tank was also tried in various configurations, including a 4-ft width, an 8-ft width, and a wedge shape with the partition positioned diagonally across the tank. As a result of these trials, it was decided that all of the baseline runs would be performed with the partition centered so as to provide two 4-ft by 28-ft test channels for each filling of the tank.

139. The 22 tests constituting the baseline runs are summarized in Table 3. The conditions for each test are given and the primary results are tabulated for head wave velocity, cloud height, and mud flow height. In general these variables remained quite steady during each test, and consequently the values listed in Table 3 are averages measured over the test distance (i.e., 24 ft). Head wave velocity and cloud height were determined by direct observation of the tests and photographic records taken during the tests. The cloud height was defined

Table 3

Baseline Test Conditions and Results

Test Number	Water Type	Sediment Type	Bottom Type	Slurry Concentration	Discharge Velocity fps	Nozzle Angle deg	Discharge Diameter, ips in.	Discharge Height Above Bottom in.	Water Depth in.	Cloud Height in.	Mud Flow Height in.	Head Wave Velocity fps
11	Fresh	Clayey Silt	Smooth	23	4	20	1	12	24	7	3	0.257
12						0				8	4-1/4	0.258
13						90				4	2-3/4	0.192
14						20	1-1/4			7	4	0.307
15							1	6		5	2-1/2	0.232
16								18		8	4-1/2	0.247
17					2			12		6	2-1/4	0.148
18					6					7	5	0.305
19				31	4					14	0	0.0792
20				15						7	3-1/2	0.242
21		Silty Clay		23							3	0.264
22		Silty Sand								8	3-1/4	0.154
23	Fresh 8-in. Salt Layer	Clayey Silt								5	7-1/2	0.107
24	Salt										4-1/2	0.225
25	Fresh		Compatible	35						*	2-3/4	0.221
26			Smooth	27						6	3	0.238
27				23	6	90				4	3	0.228
28					4	20				*	4	0.266
29						90				*	2	0.192
30						0		30 (6-in. above surface)		9	6	0.228
32							1-in. 45-deg deflector			8	7	0.234
33						20	3/4			6	3-1/4	0.240

*Test conditions precluded measurement.

Note: No entry indicates that preceding entry still applies.

as the height of the upper boundary of visible suspension above the bottom of the tank. This height was greater than that of the mud flow because suspensions containing very low concentrations of solids were still readily visible. The mud flow height was defined as that height at which the suspended solids concentration in the flowing suspension was 1 g/ℓ. Below this height, the concentration was greater than 1 g/ℓ, and the density of the suspension was sufficient to drive a mud flow. While selection of this value to define the boundary of the mud flow was somewhat arbitrary, it was based on the characteristics of the concentration profiles obtained from sampling the mud flow.

140. A profile in which the elevation above tank bottom is plotted against sediment concentration in grams per litre is shown in Figure 25. (Profiles for all test runs are included in Appendix B.) For this profile, more than 95 percent of the sediment present in the suspension occurred at concentrations exceeding the 1-g/ℓ limit. This was typical of most of the profiles obtained.

141. The visible cloud that is seen above the mud flow is created by turbidity which involves less than 5 percent of the total sediments present. Moreover, this turbidity upwells in the head wave, thereafter losing any net forward velocity and dissociating from the mud flow. Since it was not possible to obtain velocity profiles across the flow to define its character and extent, it was decided simply to select the 1-g/ℓ limit to establish the height for computations involving gravity or inertial forces.

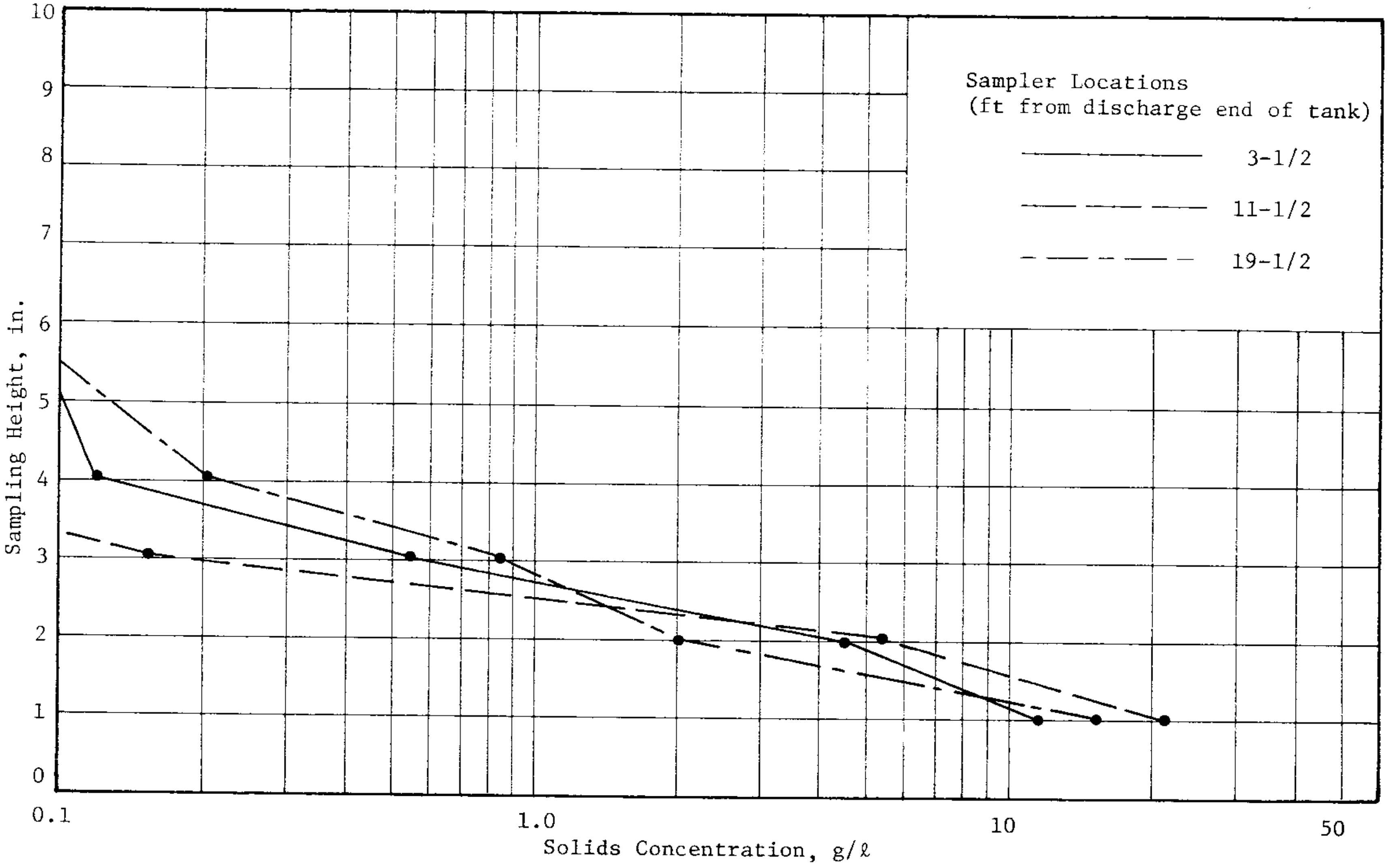


Figure 25. Typical concentration profiles (test 15)

142. The results for the five discharge configurations discussed in paragraph 99 are represented by tests 11-13, 30, and 32 and are presented in Table 4. In the above surface tests the discharge pipe

Table 4

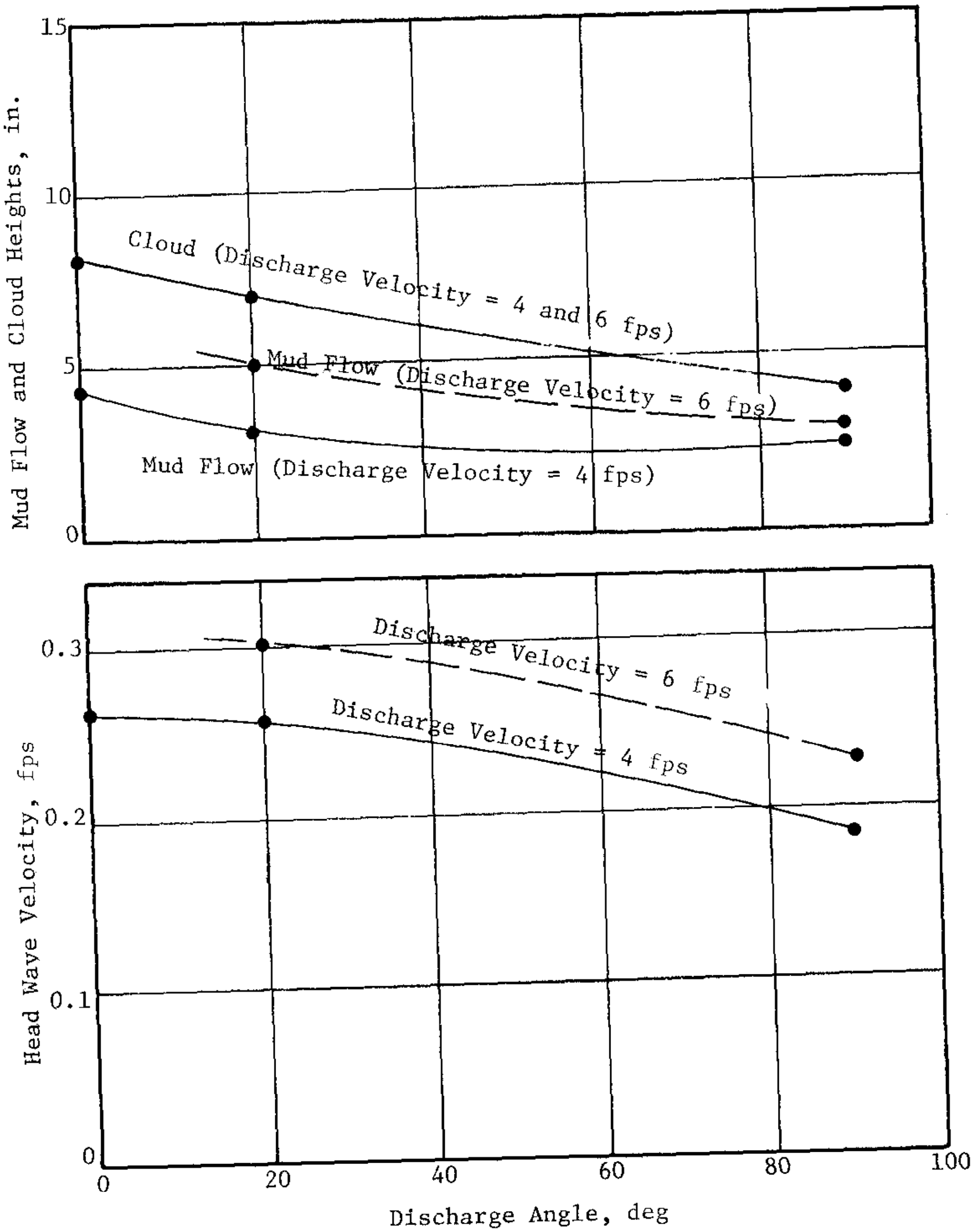
Performance of Typical Discharge Configurations

Test No.	Configuration	Head Wave Velocity fps	Mud Flow Height in.	Cloud Height in.	Turbidity Reduction Factor
30	Horizontal pipe, above surface	0.228	6	9	2.25
32	Horizontal pipe, with 45 deg baffle, above surface	0.234	7	8	2.00
12	Horizontal pipe, submerged	0.258	4-1/4	8	2.00
11	20 deg pipe, submerged	0.257	3	7	1.75
13	Vertical pipe, submerged	0.192	2-3/4	4	1.00

was 6 in. above the water surface, and in the submerged tests it was 12 in. off the bottom. Using the cloud height as the measure of turbidity generation the tests are listed in Table 4 in diminishing order with the horizontal above-surface discharge producing the greatest turbidity and the vertical submerged pipe the least. The ratio of cloud height to the vertical pipe cloud height represents the factor by which the turbidity of a configuration can be reduced by using a vertical pipe discharge. These values are listed in Table 4. The horizontal above-surface discharge produced the highest cloud probably because of the greater potential energy of the jet. The 45 deg baffle distributed the slurry across the channel but the Reynolds number of the discharge slurry was not great enough to create spray and the attendant surface turbidity observed in the field. The horizontal and 20 deg submerged configuration showed the strong directional characteristics of discharge flows aimed down the tank. The 20 deg submerged pipe generated the least turbidity of the directional configurations. The vertical submerged pipe produced the lowest cloud of any pipe configuration. From all appearances this was due to the fact that the energy of the discharge jet was spread evenly over a 360 deg front beyond impingement and displayed no prominent directional characteristics. The turbidity reduction factors indicate that the vertical submerged pipe is 2.25 times as effective as the horizontal above-surface discharge and 1.75 times as effective as the 20 deg. submerged pipe. The 20 deg. submerged pipe is seen to be 1.28 times more effective than the horizontal above-surface discharge.

143. Experimental results from the baseline runs are shown in the curves, Figures 26-31. These curves show the primary dependent variables, head wave velocity, cloud height, and mud flow height, as functions of each of the test conditions that were varied in the test matrix. The curves do not include the results of the above-surface tests, the salt water tests, nor the test using a sediment bottom, which are presented later. These results are presented in Table 3 (Tests 23-25, 30, 32) and are discussed in a later section.

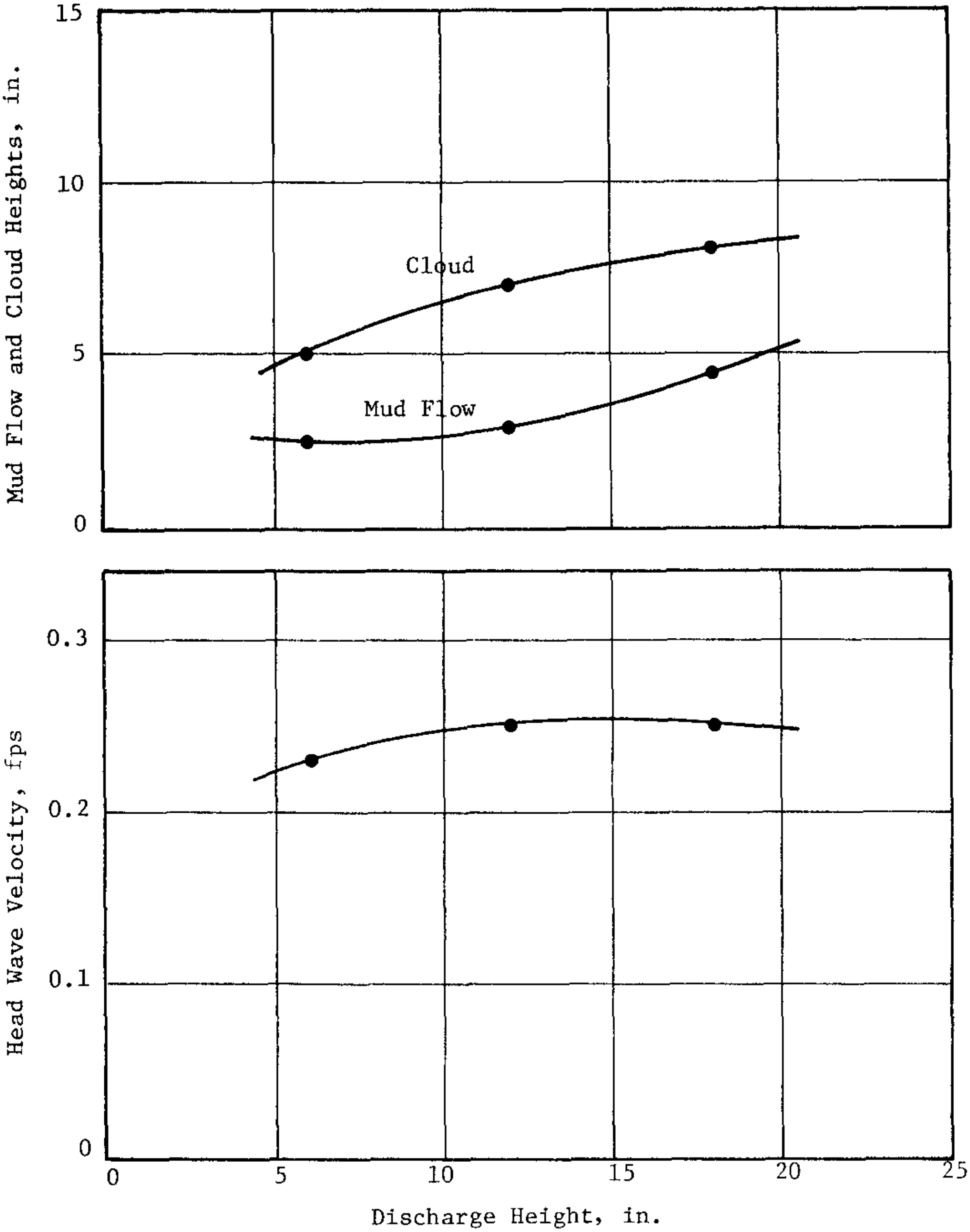
144. To facilitate comparing trends among the variables, the mud flow and cloud heights are presented on the same plot, which in



Discharge Angle = abscissa
Discharge Height Above Bottom = 12 in.
Discharge Pipe Diameter = 1 in.

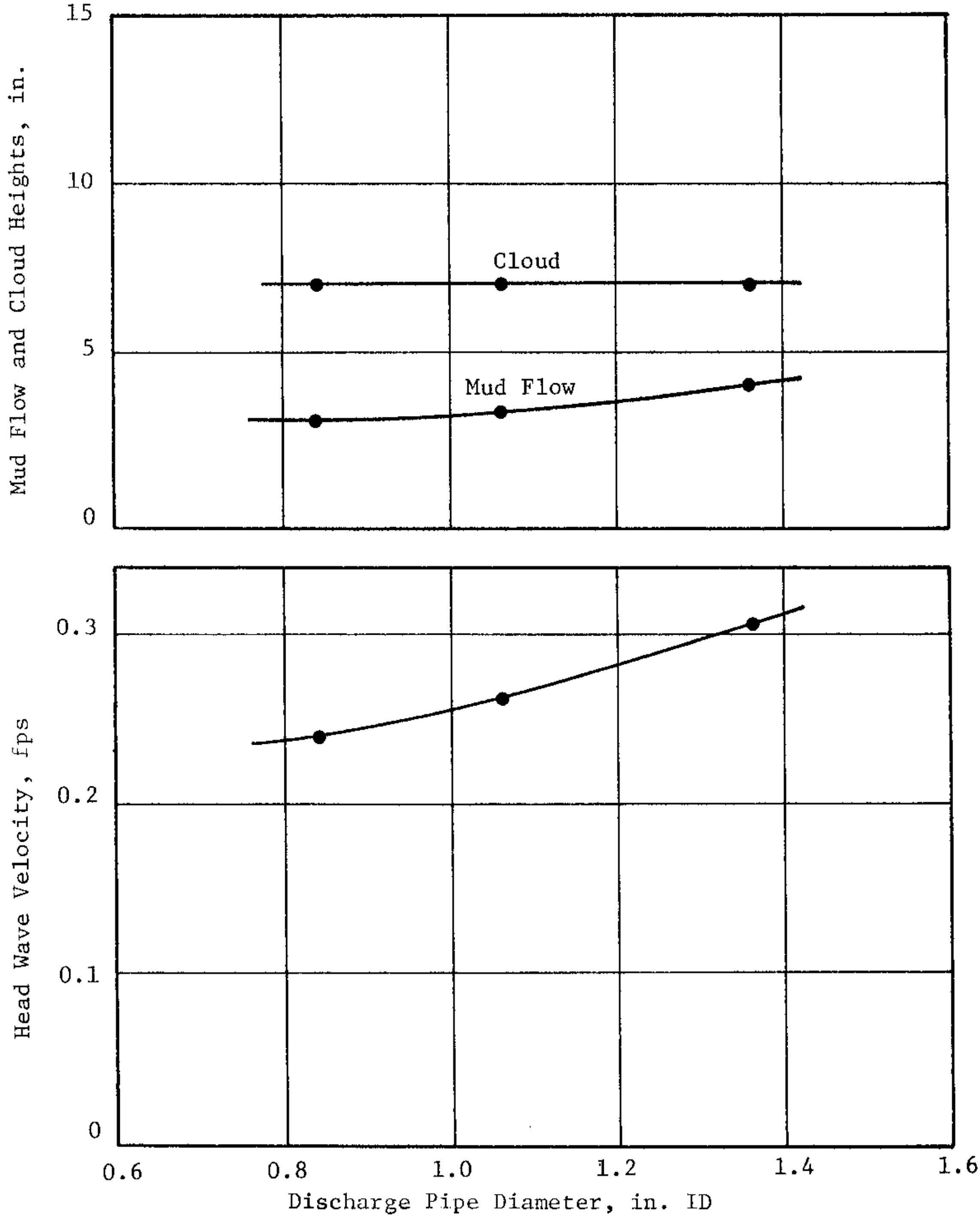
Discharge Velocity = ordinate
Sediment = Clayey Silt
Concentration = 23% solids by wt.

Figure 26. Effect of varying discharge angle



Discharge Angle = 20 deg
Discharge Height = abscissa
Discharge Pipe Diameter = 1 in.
Discharge Velocity = 4 fps
Sediment = Clayey Silt
Concentration = 23% solids by wt.

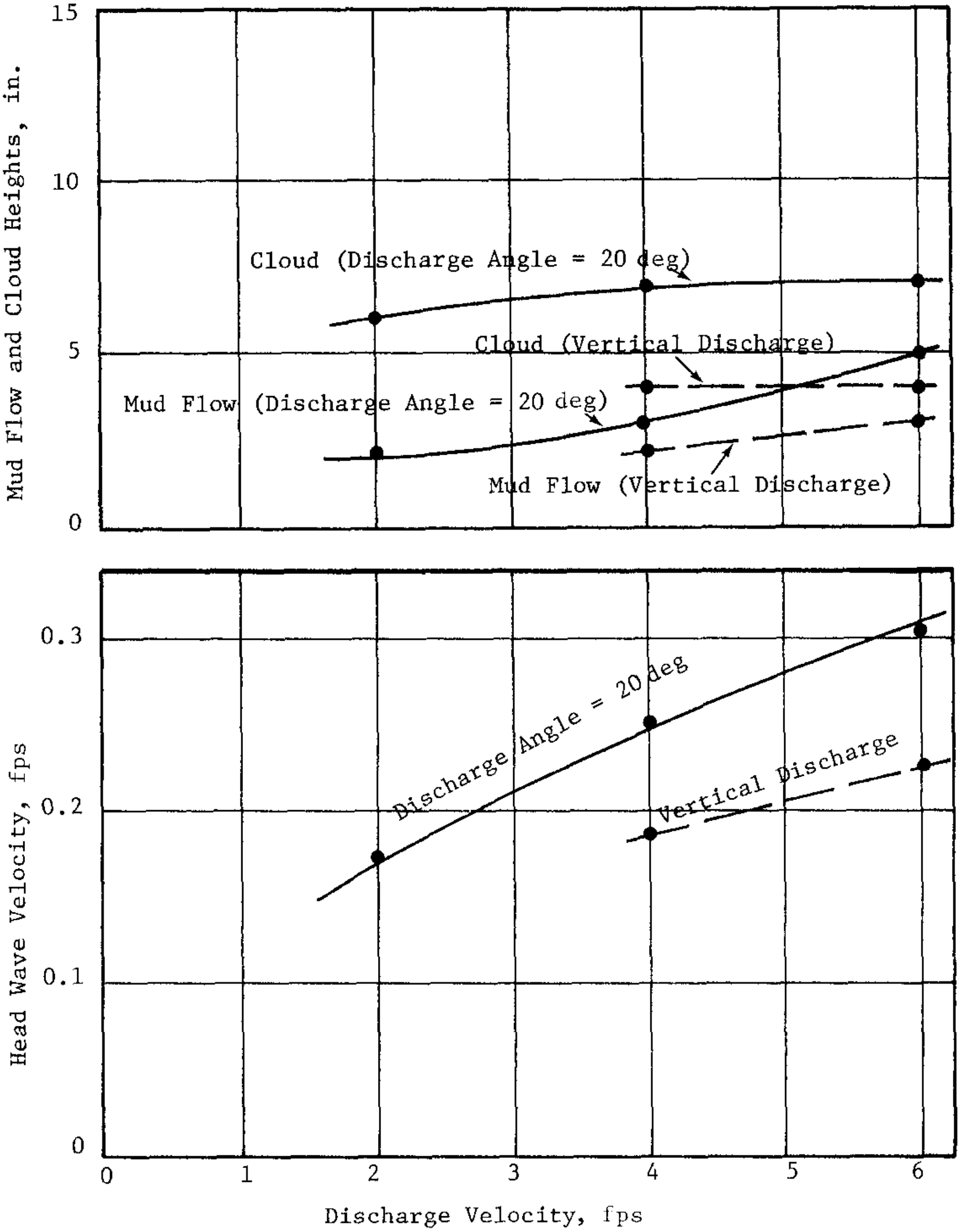
Figure 27. Effect of varying discharge height



Discharge Angle = 20 deg
Discharge Height = 12 in.
Discharge Pipe Diameter = abscissa

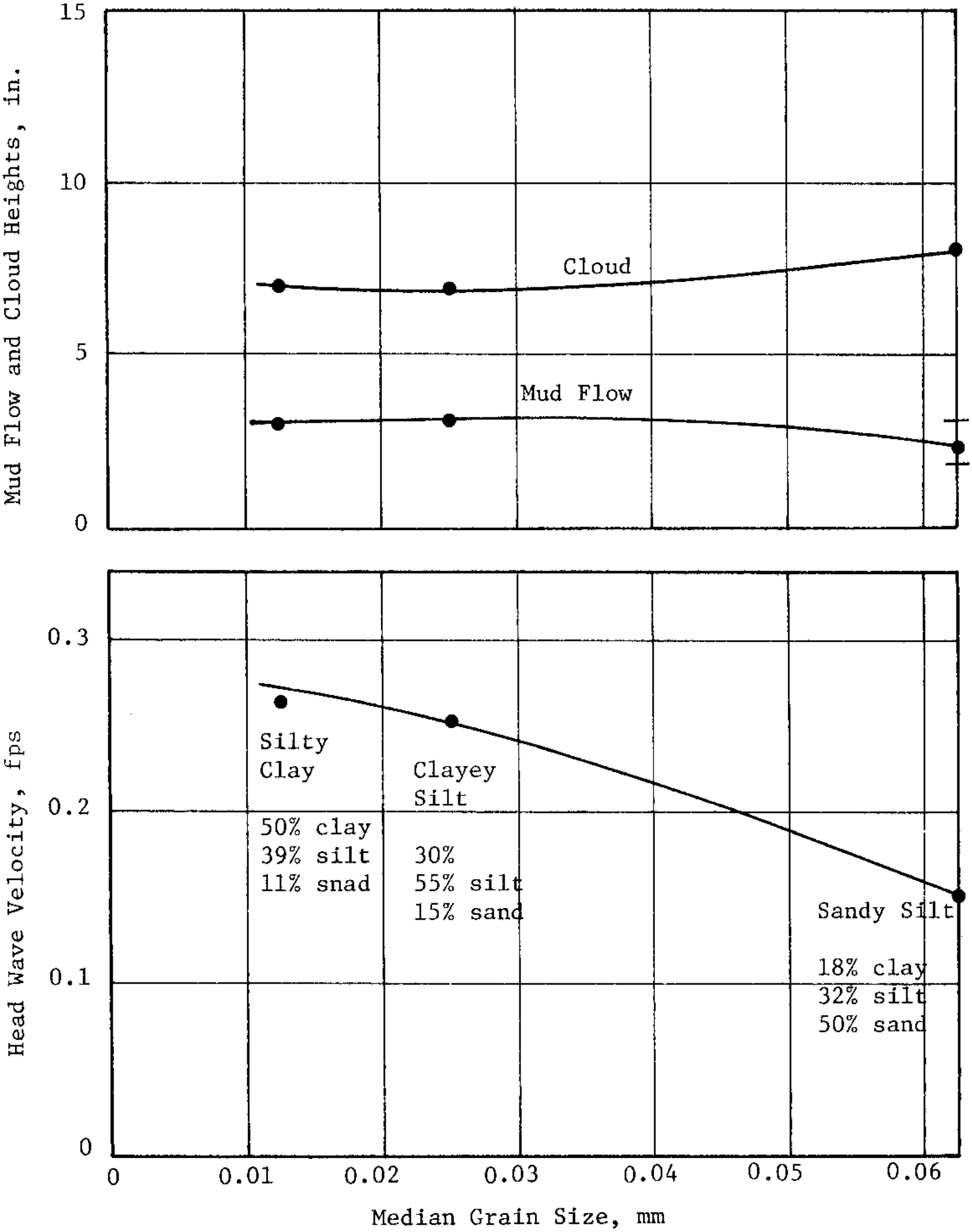
Discharge Velocity = 4 fps
Sediment = Clayey Silt
Concentration = 23% solids by wt.

Figure 28. Effect of varying discharge pipe diameter



Discharge Angle = Noted	Discharge Velocity = abscissa
Discharge Height = 12 in.	Sediment = Clayey Silt
Discharge Pipe Diameter = 1 in.	Concentration = 23% solids by wt.

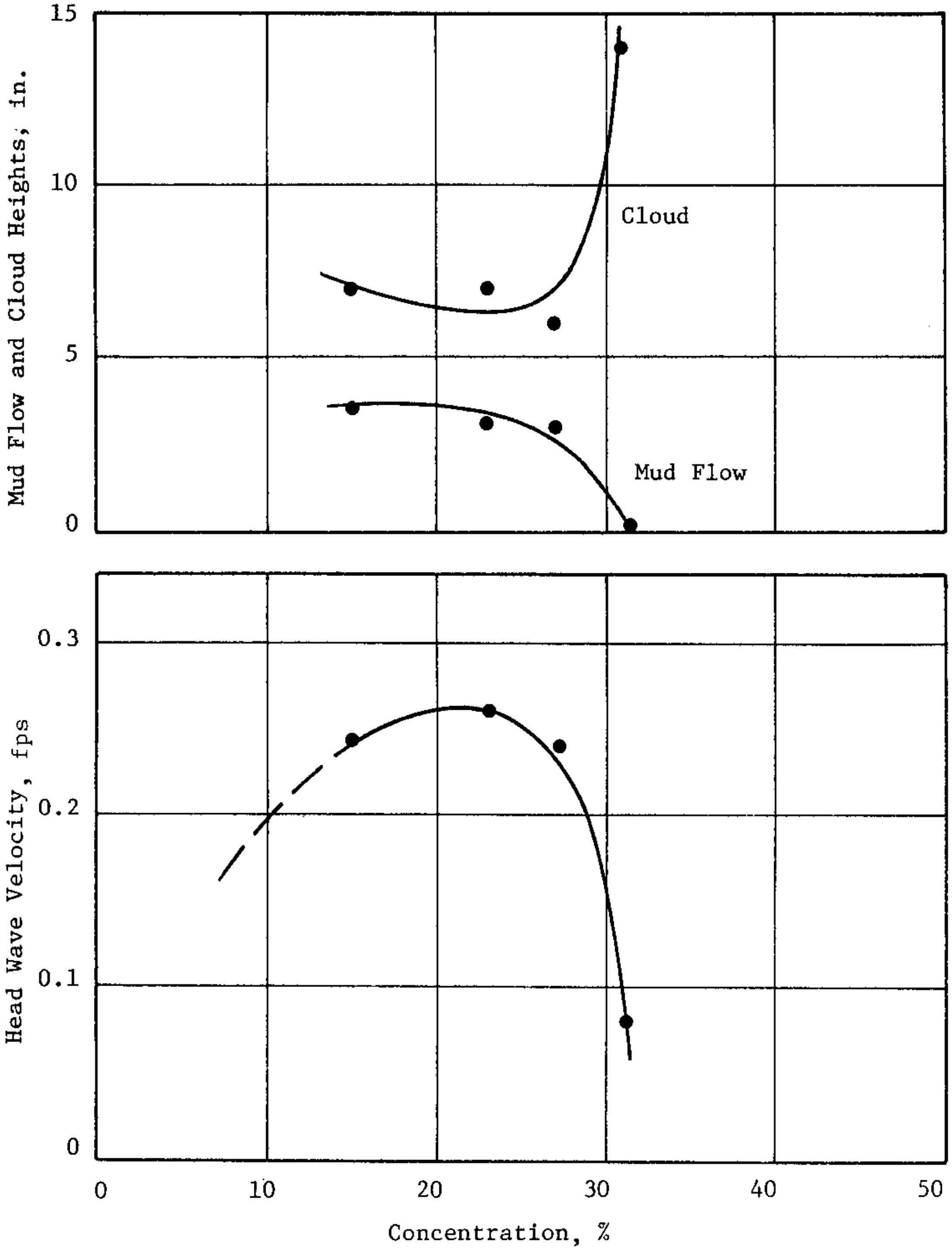
Figure 29. Effect of varying discharge velocity



Discharge Angle = 20 deg
Discharge Height = 12 in.
Discharge Pipe Diameter = 1 in.

Discharge Velocity = 4
Sediment = abscissa
Concentration = 23% solids by wt.

Figure 30. Effect of sediment type



Discharge Angle = 20 deg
Discharge Height = 12 in.
Discharge Pipe Diameter = 1 in.

Discharge Velocity = 4 fps
Sediment = Clayey Silt
Concentration = abscissa

Figure 31. Effect of solids concentration of discharged slurry

turn is displayed directly above the head wave velocity plot. The experimentally determined values are shown for each of the following six independent variables: (a) discharge angle, (b) discharge height, (c) discharge diameter, (d) discharge velocity, (e) sediment type, and (f) slurry concentration.

Discharge Angle

145. The discharge angle is the angle of the discharge pipe measured downward from the horizontal. Tests were run at three angles: 0 deg (horizontal), 20 deg, and 90 deg (vertical). One extra test beyond those defined by the test matrix was run with a vertical discharge and a flow velocity of 6 fps (with all other conditions remaining at baseline). The additional data provided another point at the 6-fps velocity; consequently, the effect of varying discharge angle is shown in Figure 26 for two values of discharge velocity, 4 and 6 fps.

146. As the orientation of the discharge stream changed from horizontal to vertical, there was a similar decreasing trend in the values of all three dependent variables. Inasmuch as the momentum of the discharge stream is directed parallel to the fluid mud flow when the discharge nozzle is horizontal and at right angles thereto when it is vertical, this trend in the data seems reasonable.

147. The mud flow height and head wave velocity increased with increases in the discharge velocity from 4 to 6 fps for all values of discharge angle. This is also a reasonable result since the momentum of the discharge stream is greater at the higher velocity.

148. While the height of the turbid cloud decreased by a factor of two as the discharge angle was varied from horizontal to vertical (Figure 26), it was not affected by the change in discharge velocity. This insensitivity is discussed in the section on the effect of discharge velocity.

Discharge Height

149. Tests were run with the discharge pipe positioned at elevations of 6, 12, and 18 in. above the tank bottom. The effects of the discharge height are presented in Figure 27. Both cloud height and mud flow height increased as the discharge height was increased. This was probably caused by the increased energy of the jet prior to impact with the bottom. The head wave velocity, on the other hand, appeared to be less affected by discharge height. There was some increase between 6 and 12 in., but between 12 and 18 in., there was no significant change. Since the head wave velocity is a function of both mud flow height and density, this result suggests that an increase in the one has been offset by a decrease in the other.

Discharge Pipe Diameter

150. Three different pipe sizes were used to determine the effects of pipe diameter on the mud flow characteristics: 3/4-, 1-, and 1-1/4-in. standard pipe sizes with actual inside diameters of 0.824, 1.049, and 1.380 in., respectively. The effects of discharge diameter are shown in Figure 28. The height of the visible cloud did not vary significantly in the three runs, while the height of the mud flow increased somewhat

with increasing discharge diameter. The head wave velocity also increased somewhat. Since the flow velocity was maintained at 4 fps for these three runs, the flow rates were different in each case (proportionate to diameter squared). The momentum of the discharge stream, therefore, increased also with the diameter of the discharge pipe. The increase in the mud flow height was probably caused by greater entrainment of water as the perimeter of the jet increased with diameter. The increase in head wave velocity was probably the result of the combined effects of the increasing momentum in the discharge stream and the mud flow height.

Discharge Velocity

151. The results of varying the discharge velocity using 2, 4, and 6 fps are presented in Figure 29. Again, because an extra run not defined by the baseline test matrix was conducted for the combination of a vertical discharge with a flow velocity of 6 fps, the results can be presented parametrically for two nozzle positions, 20 deg and vertical. As was the case for pipe diameter variations, the cloud height appeared little affected by variation of the discharge velocity. Since both diameter and velocity affect the discharge stream momentum (whereas nozzle angle and height do not), these results seemed to suggest that discharge momentum influences the mud flow height and head wave velocity more strongly than it does the height of the overlying turbid cloud, which is generated above the mud flow. Both mud flow height and head wave velocity increased about proportionally with the discharge stream velocity. This again suggested that the cause is the combination of increased entrainment and discharge momentum. The distinct influence

of nozzle orientation already evident in Figure 26 is again displayed in Figure 29. Rotation of the nozzle from 20 deg to vertically downward had a strong influence on all three dependent variables.

Sediment Type

152. The sediment characteristics were varied about the baseline condition by adding kaolin to obtain a clay and sand to obtain a silty sand. The results of three tests performed with the different sediment types are shown in Figure 30 plotted against median grain size. Grain size had little influence on either the mud flow height or the cloud height. However, because of settling during the silty sand run, there was considerable variation in the height of the 1-g/ℓ concentration in the flow; hence, there was not a single representative mud flow height. Nevertheless, the range of values was indicated, and the average was used to represent the flow height for that run. The head wave velocity decreased appreciably as the median grain size increased. This is also likely to be the result primarily of settling. During the silty sand run, a mound of larger particles accumulated at the area of impact, indicating that a greater fraction of solids was settling than occurred in other tests. Because a lesser fraction of the solids remained in suspension, the density of the mud flow was less, the driving force was decreased, and the head wave velocity was therefore less.

Solids Concentration

153. Using the baseline sediment, water content was varied to obtain slurries of four different solids fractions: 15, 23, 27, and 31 percent. The results of tests conducted with these slurries are shown in Figure 31. Cloud height, mud flow height, and head wave velocity

were little affected by slurry concentration in the three tests at 15, 23, and 27 pcs. However, these properties changed dramatically at 31 pcs. In this run, the slurry, which was very stiff or rigid on exiting the discharge nozzle, tended to remain agglomerated in chunks which did not entrain water to dilute the slurry and maintain a well-formed jet. Instead, these chunks were deposited leaving very little material in suspension to generate a mud flow. The turbidity cloud that was generated in the 31-pcs test billowed up to a height greater than observed in any other test. The head wave itself did not travel the full length of the tank, stopping about 8 ft short of the end. In addition, no water samples (which were taken no closer to the bottom than 1 in.) showed concentrations above 1 g/ℓ. Thus, by the definition utilized, no mud flow was detected. At the beginning of the run, there may have been a transitory mud flow. However, as the suspension became rapidly diluted, the mud flow probably disappeared, and the remaining suspension of fine particles became simply a turbid cloud subject to convective diffusion.

Other Variables

154. Additional tests were run to determine whether or not salinity or a simulated natural-sediment bottom would have any significant influence on the mud flow characteristics. In test 23, a stratified 8-in. layer of salt water (at approximately 30 °/₀₀) underlay fresh water, and in test 24, all of the water was uniformly salty at 30 °/₀₀. In test 25, the bottom of the tank was covered with the same sediment as that

used in the slurry mixture in order to simulate a natural bottom. The results of these three tests are presented in Table 5 together with the baseline results for comparison.

Table 5

Effects of Salinity and Natural Sediment

Test Number	Variable: Cloud Height at end of Test, in.	Variable: Mud Flow Height, in.	Variable: Head Wave Velocity, fps
11 (Baseline)	9	3	0.26
23 (Salt and fresh water)	8	7-1/2	0.11
24 (Uniformly salty)	7	4-1/2	0.23
25 (Natural bottom)	7	2-3/4	0.22

155. The salt water layer in test 23 affected the mud flow in several distinctive ways. It appeared to confine the mud flow and the turbid suspension above the flow. The interface between the salt water and overlying fresh water acted as a barrier, not only confining the flow but preventing turbidity from upwelling above the layer. The velocity of the mud flow was also considerably influenced by the layer of salt water. During the test, a backflow of water was observed that was confined between the upper boundary of the layer and the mud flow. Apparently as the head wave moved forward, salt water confined in the stratified layer was displaced and flowed back over the head wave.

Because of the confining effect of the layer, there was a greater impedence to the mud flow, and its velocity was reduced by a factor of about two compared with that of the baseline. The mud flow height (as established by the height of the 1-g/ℓ concentration in the suspension) was significantly greater than that of the baseline run. This perhaps also can be attributed to the confining effect of the salt water layer. Apparently, the backflow within the layer promoted enough upward mixing of the suspension so that the 1-g/ℓ level of concentration was higher than normal.

156. The influence of a uniform mixture of salt water in test 24 was much less than that of the salt water layer. The mud flow height was somewhat greater than for the baseline run, and the head wave velocity was somewhat less. Since the head wave velocity was due in part to the difference in density between the suspension and the surrounding water, the fact that the saline water was denser could account for the decreased velocity. The increased mud flow height was less readily explained, however. The difference was great enough (4-1/2 versus 3 in.) to believe that it was of significance, and it may have been associated with flocculation effects promoted by the salt water.

157. Test 25, utilizing a simulated natural-sediment bottom, showed even less deviation from the baseline test. The mud flow height was essentially the same, and the head wave velocity was somewhat less. The difference in velocity may be attributed to an increased resistance to the mud flow caused by the sediment bottom compared with the smooth tank bottom.

158. Insofar as their implications for the design of a submerged discharge system, these results are of no great significance. Moreover, within reasonable limits, they do not exhibit effects that are strong enough to cause any concern about the validity of full-scale predictions. However, the behavior of the mud flow in the salt layer may be of significance in understanding what might happen to a mud flow and associated turbidity in the special case of discharging dredged material where a salt water wedge is present.

Mud Flow Momentum Flux

159. The momentum of the mud flow is a property or characteristic variable that can be derived from the primary variables that were measured in the experiments and is defined by the following equation:

$$M_f = \rho h W V^2 \tag{22}$$

where ρ is the bulk density of the suspension, h is the height of the flow, W is the tank width, and V is the flow velocity. In these experiments, both density and velocity vary with height of the mud flow, and there is no well-defined boundary between the suspension participating in the density flow and that merely present as turbidity above the flow. Nevertheless, useful and consistent correlations can be obtained using momentum flux as determined from the following data: (a) an average density obtained from the concentration profiles, (b) a mud flow height based on the 1-g/ℓ concentration level, and (c) the velocity of the leading edge (head wave) of the flow.

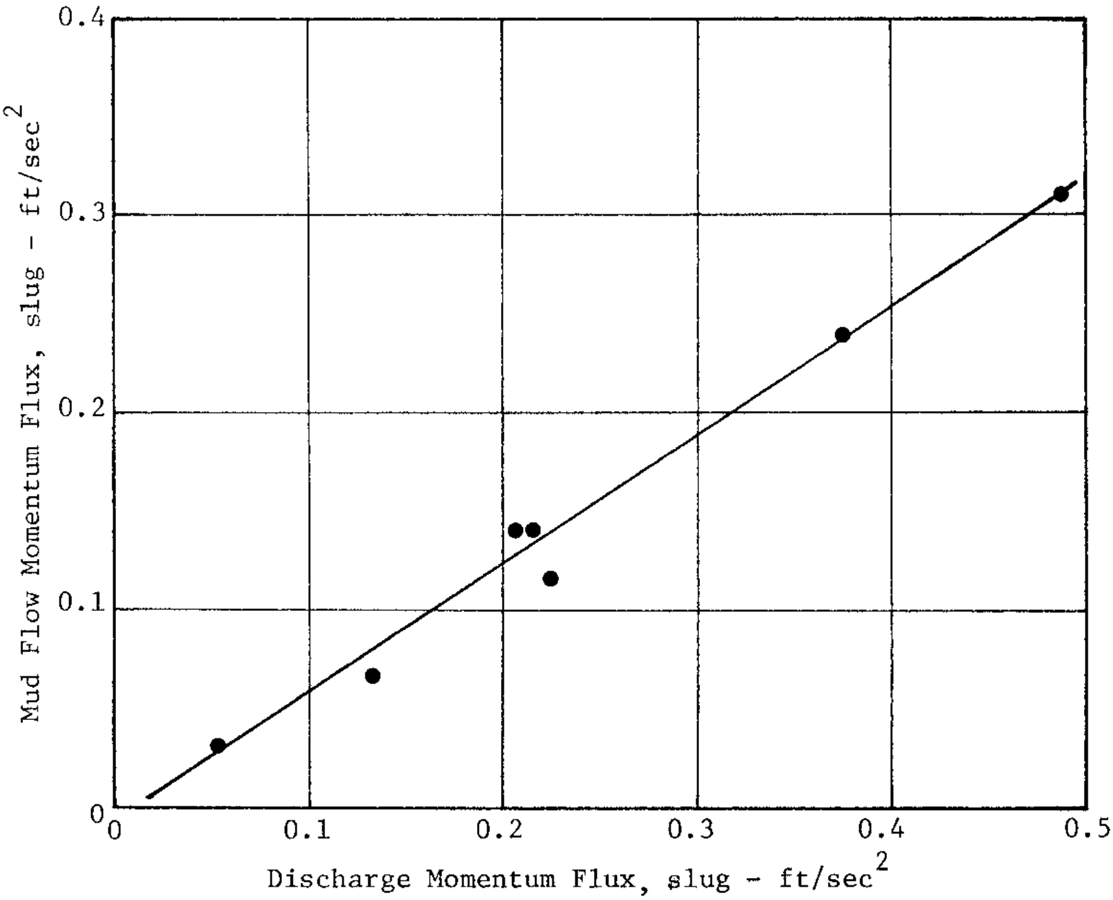
160. A momentum flux can be calculated for the slurry discharge stream with much less uncertainty about the value of the parameters. The density is simply the average slurry density and is determined by the solids concentration; the area is the cross-sectional area of the discharge pipe; and the velocity is determined by the flow rate.

161. In the baseline program, there were eight runs in which varying the parameter affected the momentum flux of the discharge stream directly. Other parameters which did not effect the discharge momentum but could influence the mud flow momentum, such as height of the discharge above the bottom and discharge stream direction, were held constant in these runs. Run 11 was the baseline test about which all other parameters were varied. Tests 14 and 33 employed different nozzle diameters, thus affecting the discharge area. Tests 17 and 18 were runs with discharge velocities less than and greater than the baseline condition, respectively. Tests 19 and 20 utilized different concentrations of solids in the slurry, thus affecting the density of the discharge stream. Test 26 provided a fourth value of slurry density. Of these eight tests, valid data allowing calculation of both mud flow and discharge momentum flux were available from seven. In Test 19, which was the highest slurry concentration, agglomerate particles fell out of the discharge stream; and the resulting mud flow was totally atypical. Thus, data from this test could not be used for the momentum flux calculations.

162. In Figure 32, the momentum flux of the mud flow is plotted against the discharge momentum flux for the seven runs. A straight line, determined by the method of least squares, is drawn through the data points. The correlation coefficient for these data is 0.99, indicating a very close linear relationship between momentum of the mud flow and that of the discharge stream. The slope of the straight line (approximately 0.65) is less than one, which indicates that the momentum in the observed mud flow is less than that in the discharge stream. This is reasonable because the momentum should be reduced by settling. In addition, the slurry divides on impact with the bottom so that only part of the suspension moves in the direction of the sampling and observation points.

163. Based on these data, it would be reasonable to conclude that in a full-scale dredging situation utilizing a submerged discharge pipe, there would be a similar relationship between the discharge momentum and the resulting mud flow momentum. Many factors, including the geometry, bottom conditions, and sediment type, would influence the actual numerical relationship, however. The high degree of correlation also lent credence to the sampling methods utilized, and helped to support some of the underlying assumptions and simplifications that were necessary to derive a momentum flux from the primary data.

164. The degree of correlation between the primary dependent variables and the discharge momentum flux provided additional evidence of the validity and consistency of the test results. The cloud height, mud flow height, and head wave velocity are plotted against the discharge



Discharge Angle = 20 deg
Discharge Height = 12 in.
Discharge Pipe Diameter = Varies

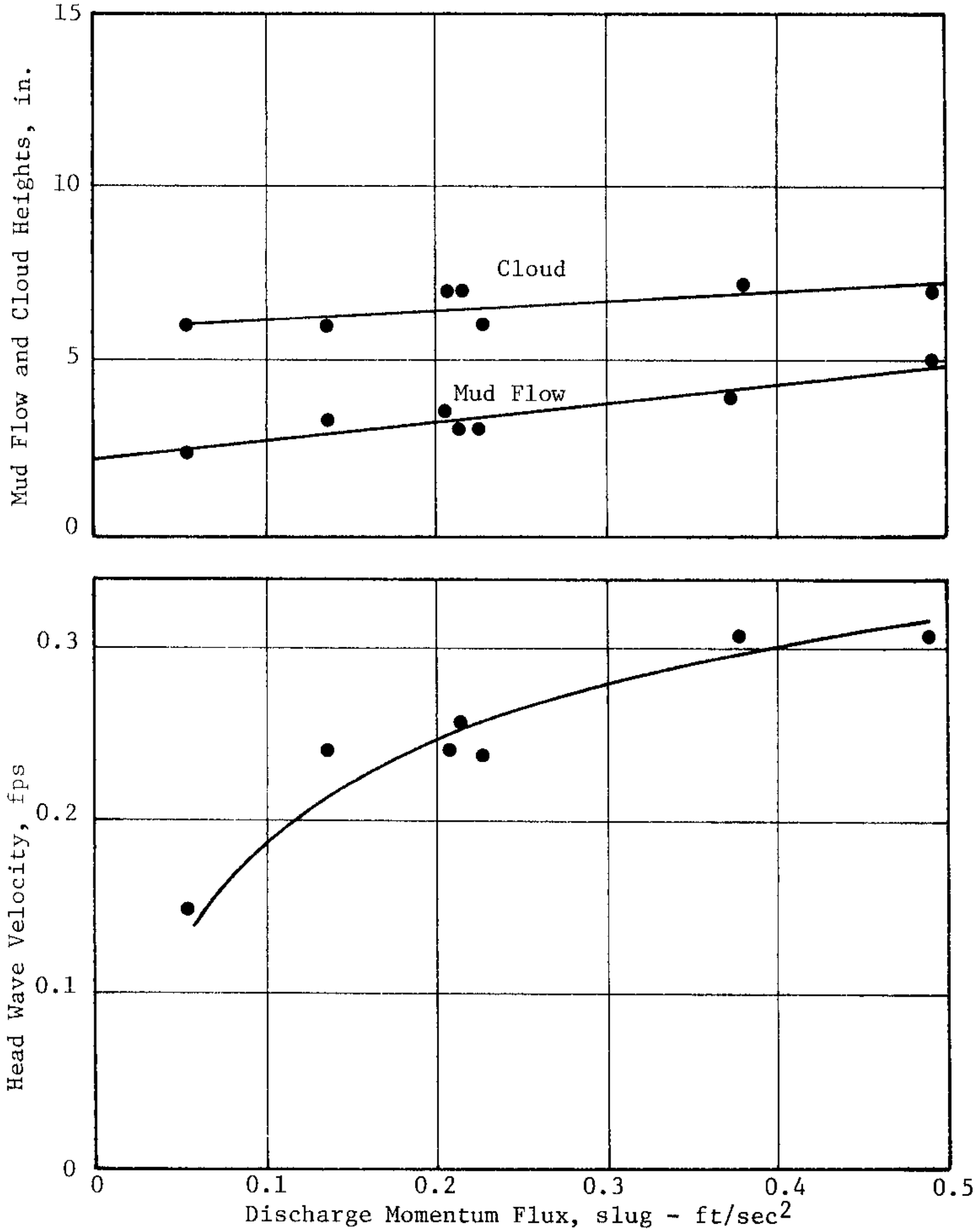
Discharge Velocity = Varies
Sediment = Clayey Silt
Concentration = Varies

Figure 32. Momentum flux correlation

momentum in Figure 33 for the same seven runs in which only parameters affecting discharge momentum were varied. The cloud and mud flow heights appeared to be linear functions of the momentum with correlation coefficients of 0.68 and 0.94, respectively. The head wave velocity required a curve to fit the data, and because it was consistent with the definition of momentum flux given in equation 22, a parabola was used as shown in the figure. The correlation coefficient for this regression was 0.85 (based on a least-squares fit to a logarithmic plot of the data).

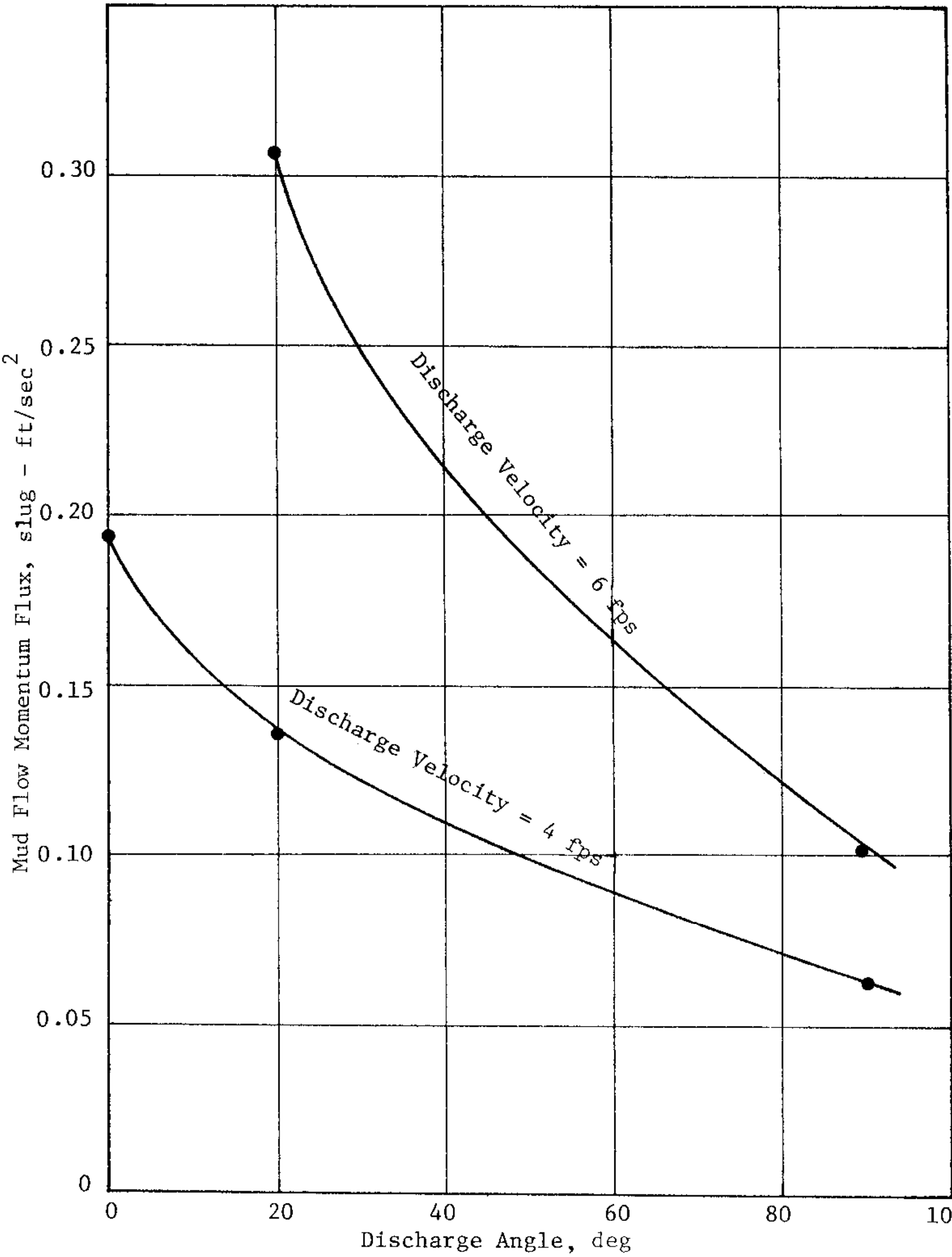
165. In Figures 34-39, the mud flow momentum flux is shown plotted against the six test variables for which the primary test results have already been presented: (a) discharge angle, (b) discharge height, (c) discharge pipe diameter, (d) discharge velocity, (e) median grain size, and (f) sediment concentration. In all cases, the data showed smooth variations and the trends were reasonable.

166. These results can be used to aid in full-scale predictions for geometrically similar situations. Based on Froude scaling, the momentum flux can be predicted directly by multiplying the test value of the flux by the cube of the scale factor. Since head wave height and velocity can be obtained for the full-scale situation by similar procedures, the momentum flux correlations can be used for estimating full scale mud flow properties.



Discharge Angle = 20 deg
Discharge Height = 12 in.
Discharge Pipe Diameter = Varies
Discharge Velocity = Varies
Sediment = Clayey Silt
Concentration = Varies

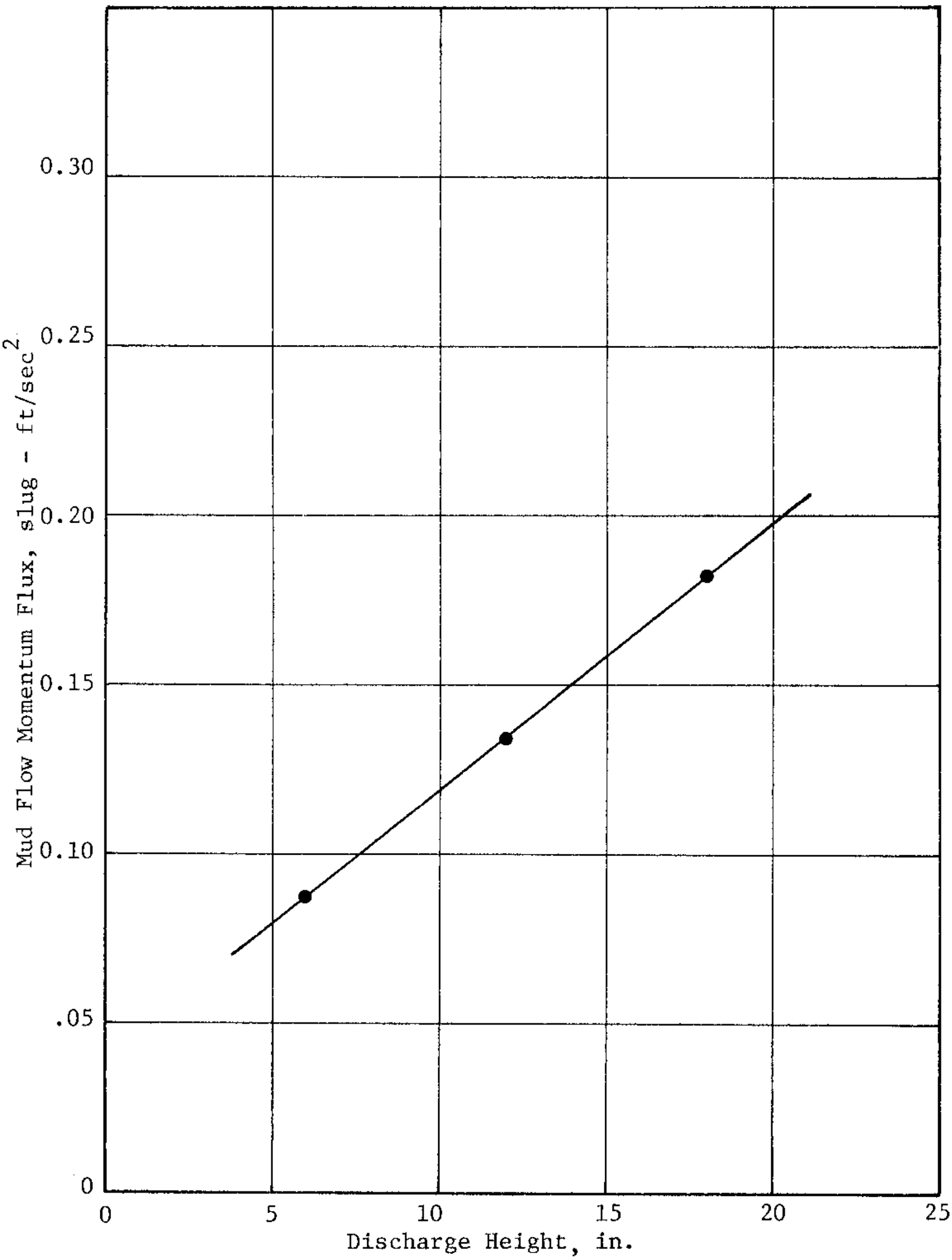
Figure 33. Discharge momentum flux correlations



Discharge Angle = abscissa
Discharge Height = 12 in.
Discharge Pipe Diameter = 1 in.

Discharge Velocity = noted
Sediment = clayey silt
Concentration = 23 percent solids by weigh

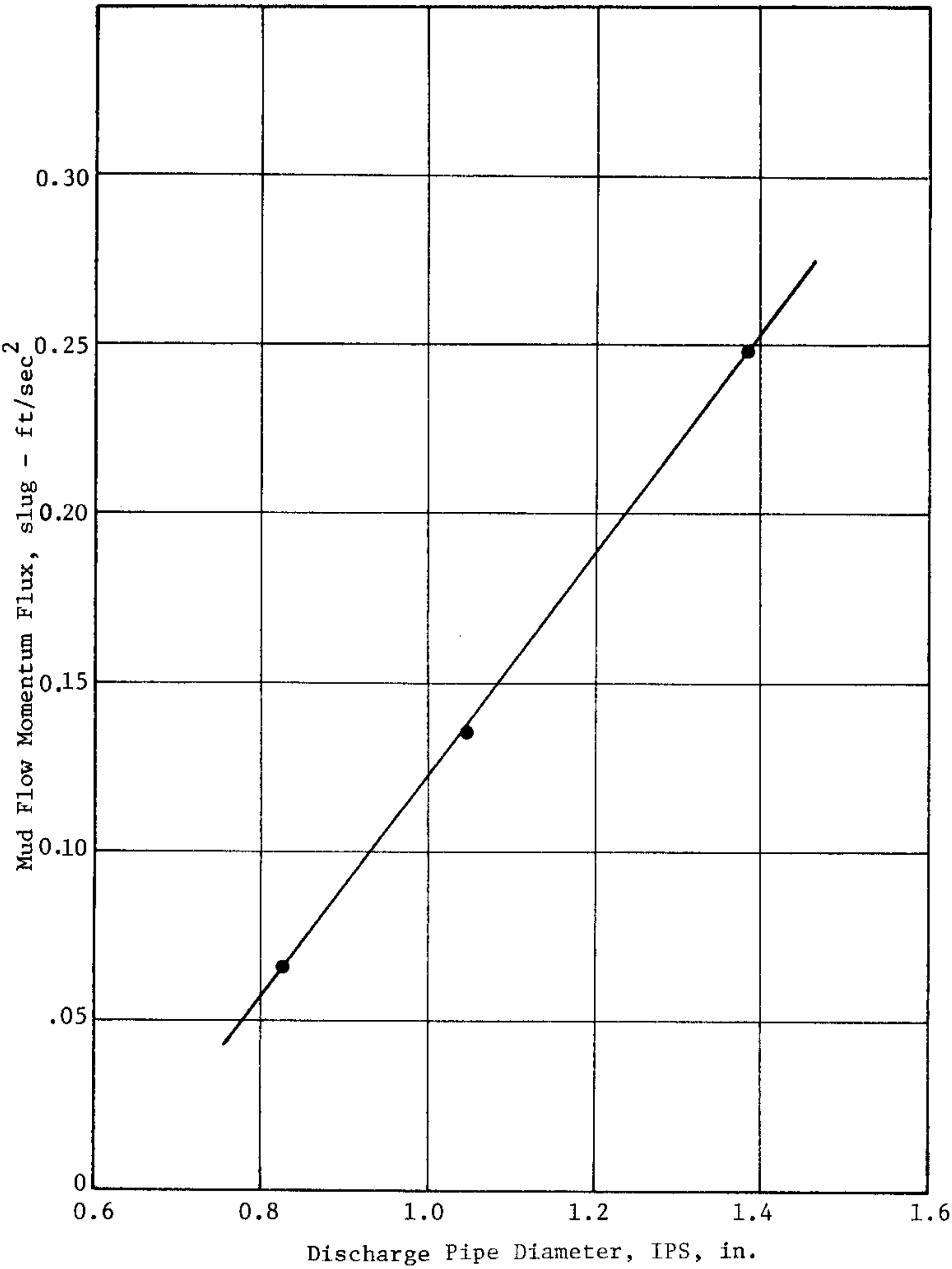
Figure 34. Mud flow momentum flux versus discharge angle



Discharge Angle = 20 deg
Discharge Height = abscissa
Discharge Pipe Diameter = 1 in.

Discharge Velocity = 4 fps
Sediment = clayey silt
Concentration = 23 percent by weight

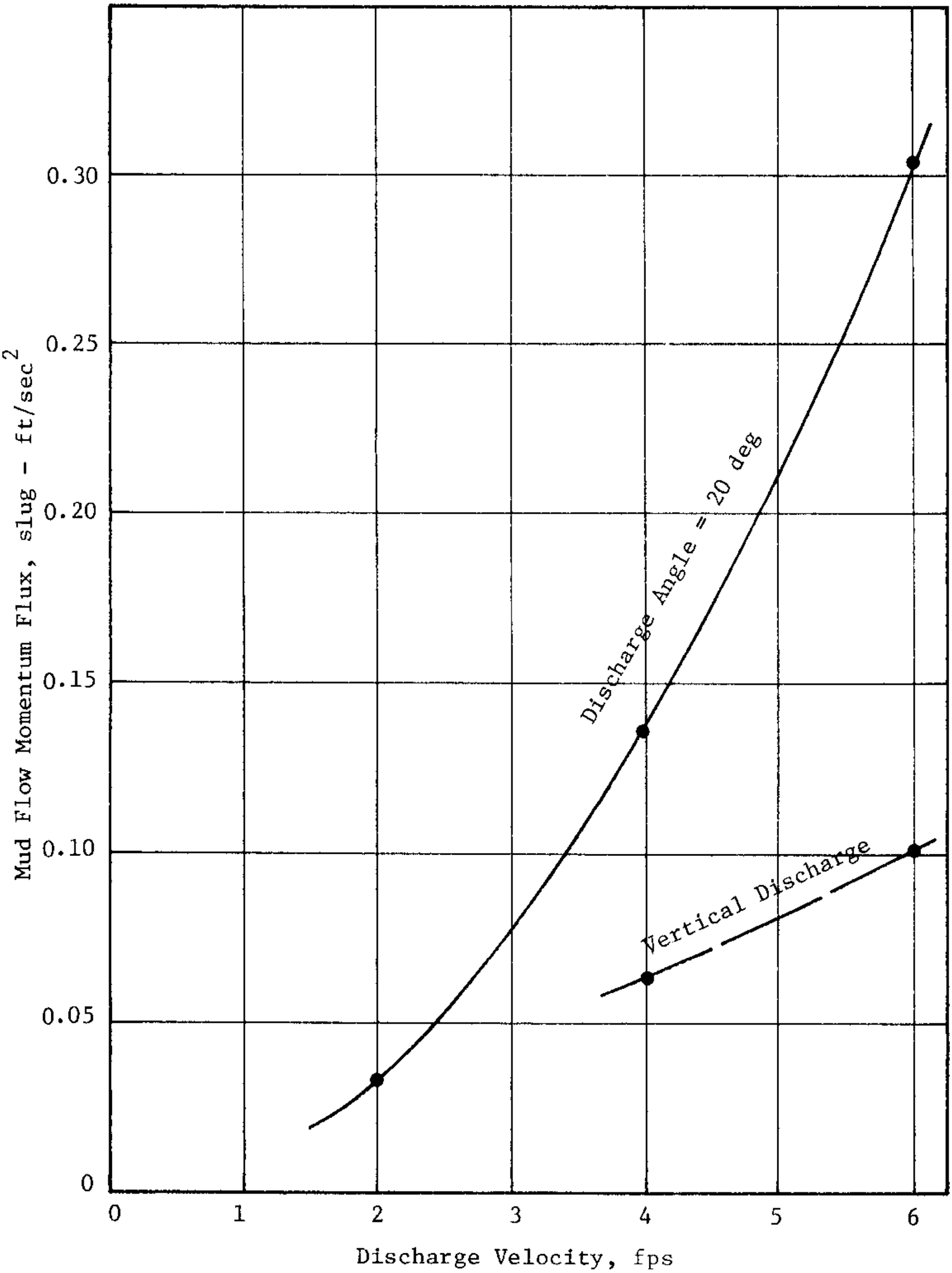
Figure 35. Mud flow momentum flux versus discharge height above bottom



Discharge Angle = 20 deg
Discharge Height = 12 in.
Discharge Pipe Diameter = abscissa

Discharge Velocity = 4 fps
Sediment = clayey silt
Concentration = 23 percent solids by weight

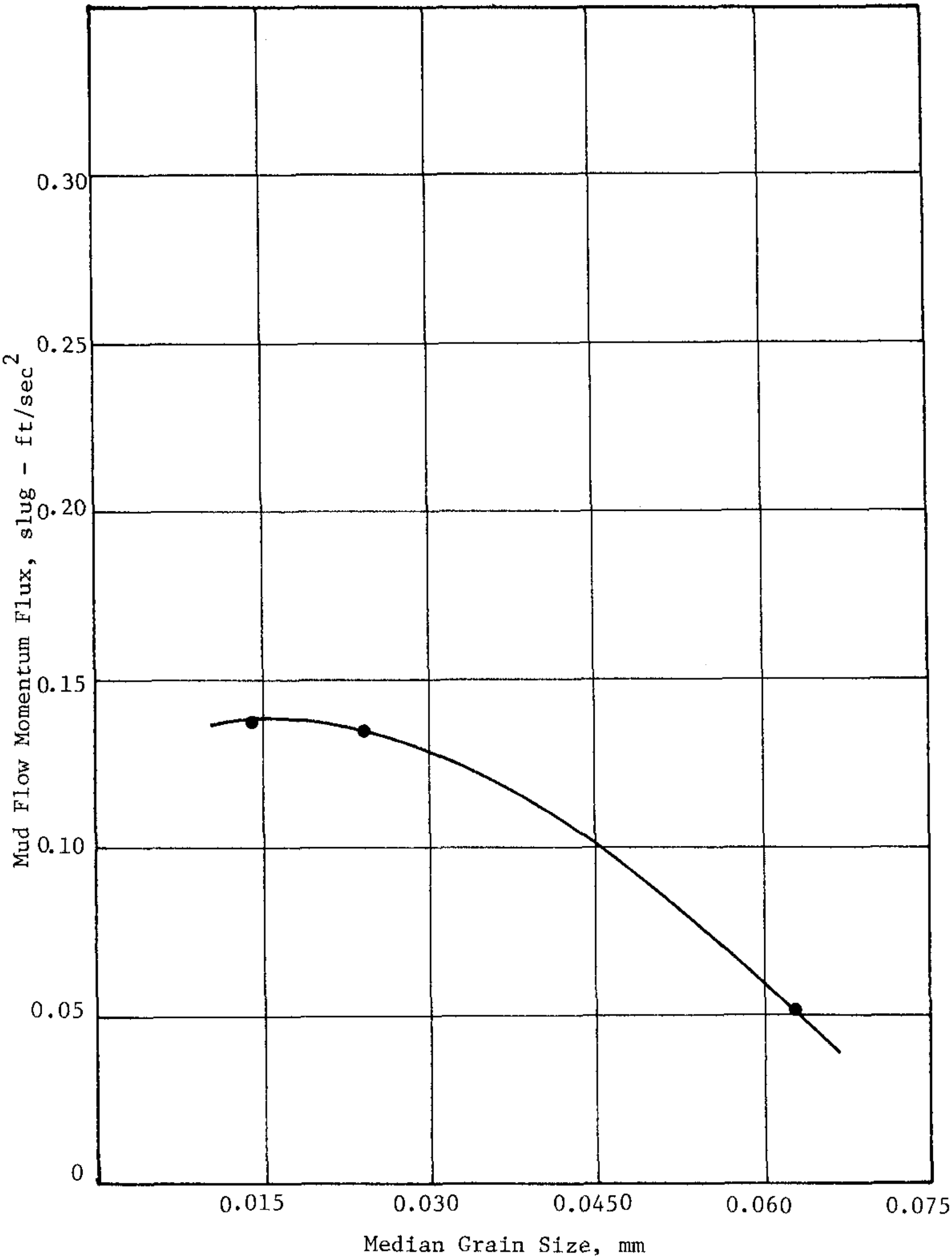
Figure 36. Mud flow momentum flux versus discharge pipe diameter



Discharge Angle = 20 deg
Discharge Height = 12 in.
Discharge Pipe Diameter = 1 in.

Discharge Velocity = abscissa
Sediment = clayey silt
Concentration = 23 percent solids by weight

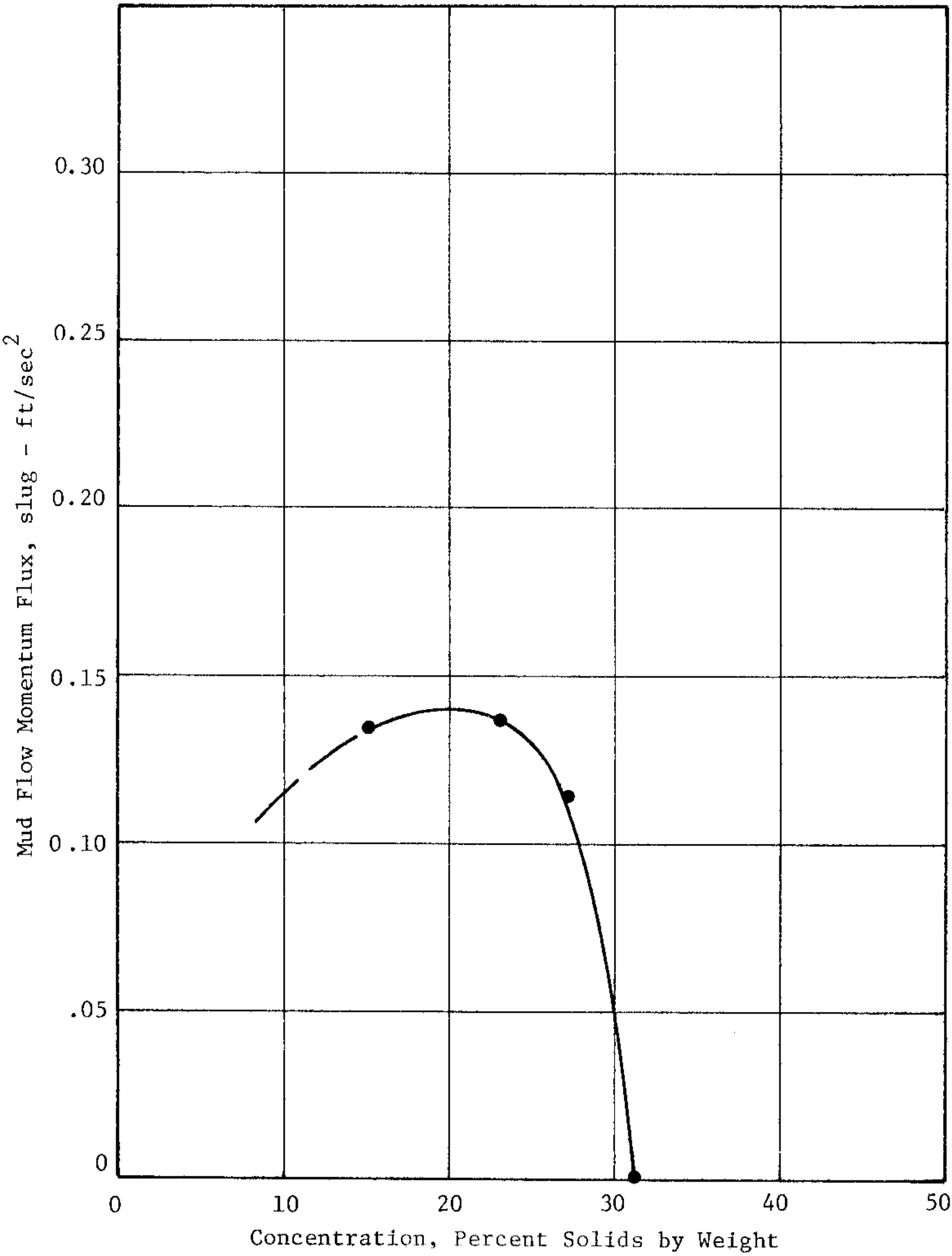
Figure 37. Mud flow momentum flux versus discharge velocity



Discharge Angle = 20 deg
Discharge Height = 12 in.
Discharge Pipe Diameter = 1 in.

Discharge Velocity = 4 fps
Sediment = abscissa
Concentration = 23 percent solids by weight

Figure 38. Mud flow momentum flux versus sediment median grain size



Discharge Angle	= 20 deg	Discharge Velocity	= 4 fps
Discharge Height	= 12 in.	Sediment	= Sandy Silt
Discharge Pipe Diameter	= 1 in.	Concentration	= abscissa

Figure 39. Mud flow momentum flux versus sediment concentration

CHAPTER V: PROCESSOR TEST PROGRAM

Purpose and Scope

167. On completion of the series of tests utilizing a simple submerged open pipe (the baseline test program), another series of tests was run in order to evaluate the effectiveness of four different types of discharge devices (or processors) designed to reduce turbidity generated by open-water pipeline disposal operations. These were designated the shroud, the weir, the plenum, and the diffuser.

168. A matrix of tests was arranged to quantify the relative performance of each processor design with respect to the simple open pipe configuration. Only the finally selected configuration (diffuser) was subjected to the full battery of tests in order to establish its superiority over the open pipe termination. The others were tested only to the extent required to eliminate the less promising candidates based on their performance and applicability to full-scale operational conditions.

169. A total of 22 runs were conducted for the processor test program. (These are tabulated in the section describing test results.) The test equipment and procedures, sampling apparatus, and photographic coverage were essentially the same as those employed in the baseline test program.

Selection and Design of Processor Models

170. Four different types of processors, representing diverse approaches, were selected for test and evaluation. All were intended to reduce turbidity generation by achieving the following objectives:

- a. Discharge the dredged material near the bottom.
- b. Discharge the dredged material at greatly reduced momentum (or velocity).
- c. Confine the slurry flow within the processor as its momentum is being reduced to minimize the entrainment and mixing.
- d. Maintain sufficient momentum of the dredged material at discharge to avoid undue mounding.

The processors tested are described in the following sections.

Shroud

171. The shroud (Figure 40) is a device that would be attached to a vertical open pipe to enclose the discharge jet and isolate it from the surrounding water. It is approximately cone-shaped and would be made of a heavy-duty plastic-coated fabric such as the kind used for oil confinement booms or silt curtains. In practice, the shroud would be attached to a vertical discharge pipe which would be submerged and positioned so that the shroud would be suspended a few feet off the bottom. Figure 41 shows the test model.

172. The principal potential benefit of this design is that it would be relatively inexpensive. In addition, it would not restrict

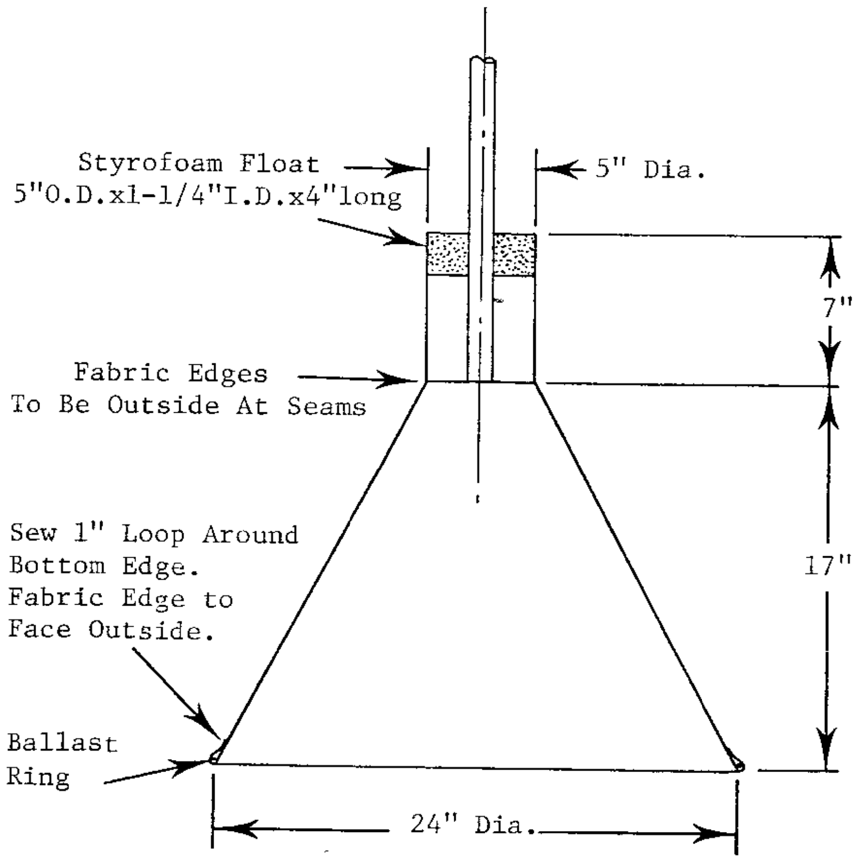


Figure 40. Shroud model fabrication sketch

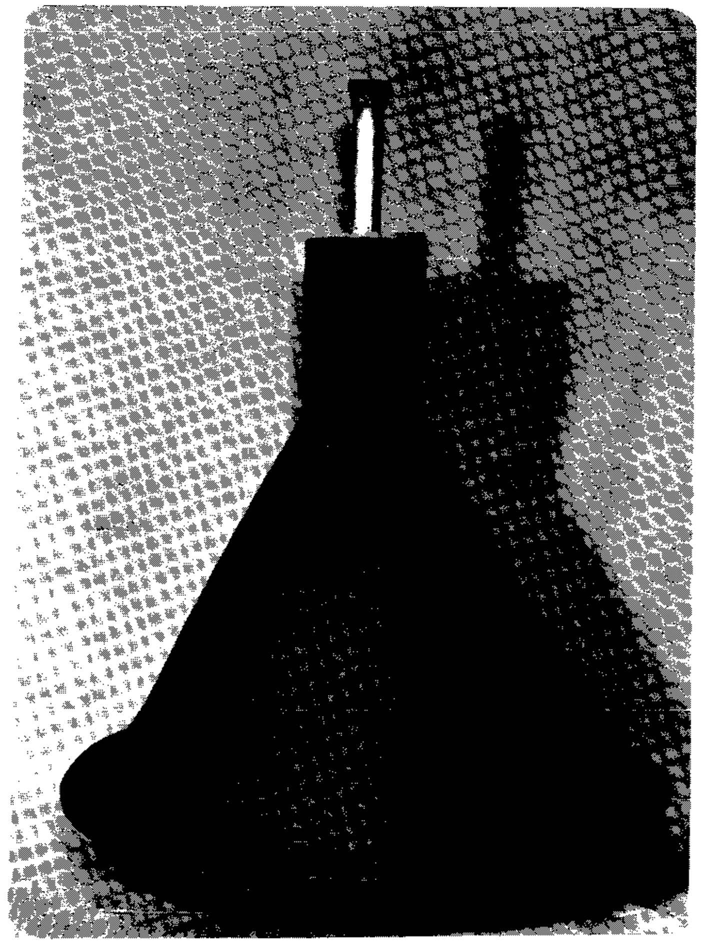


Figure 41. Shroud model

the flow and would not be clogged by occasional large solids. On the other hand in full-scale (at least 20 ft diameter by 20 ft overall height) it would be awkward to handle and would be limited to use in relatively deep water.

Cylindrical Weir

173. The weir (Figure 42 and 43) is simply a cylindrical bowl with a flat bottom and a discharge connection placed so that the dredged material enters the bowl tangentially near the bottom. The intent of this design is to reduce the momentum of the stream by two mechanisms. First, by entering tangentially, the slurry would theoretically create a vortex which would dissipate some energy by friction. Second, the effective flow area would increase as the slurry flows over the top edge of the weir, causing a reduction in the average stream velocity.

Plenum

174. This axisymmetric design (Figure 44) utilizes a large plenum chamber in which the energy and momentum of the slurry flow are partially dissipated before the slurry passes through a radial diffuser. The model, which was used in the processor tests, is shown in Figures 45a and b.

175. The discharge from the dredge pipe splashes against an impingement plate at the base of the cylindrical plenum chamber (Figure 44). The flow then reverses and travels upward through the annular space between the inlet pipe and the plenum wall. It then passes over the wall of the plenum, down through the annular passage of the diffuser,

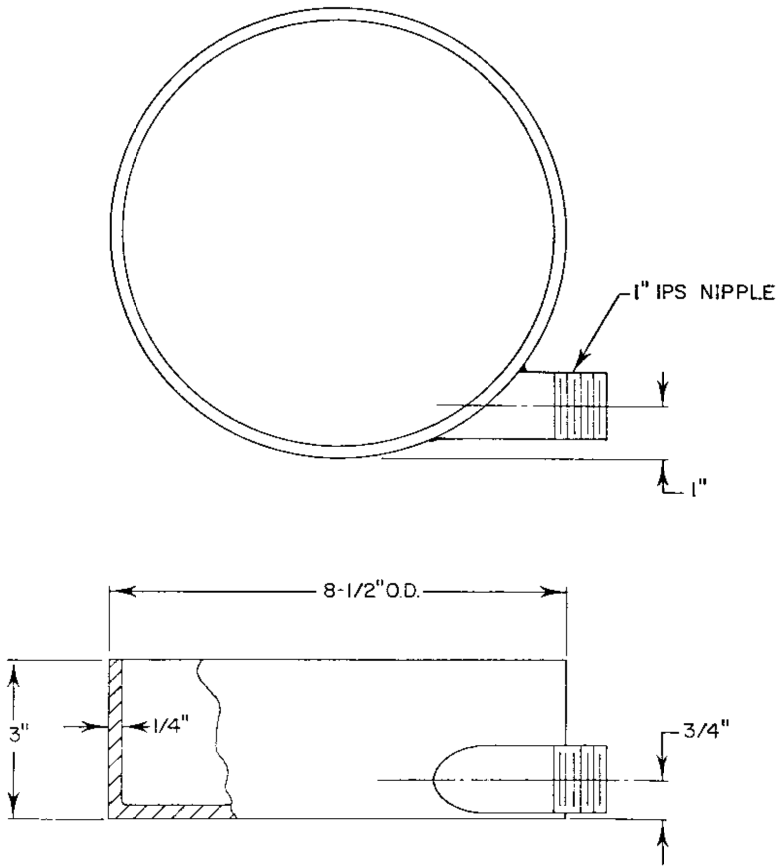


Figure 42. Weir model fabrication sketch

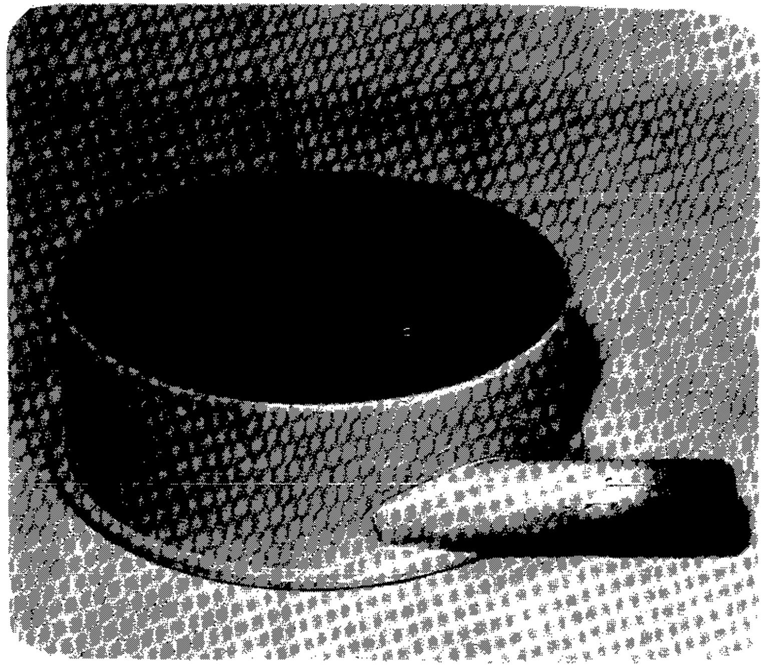


Figure 43. Weir model

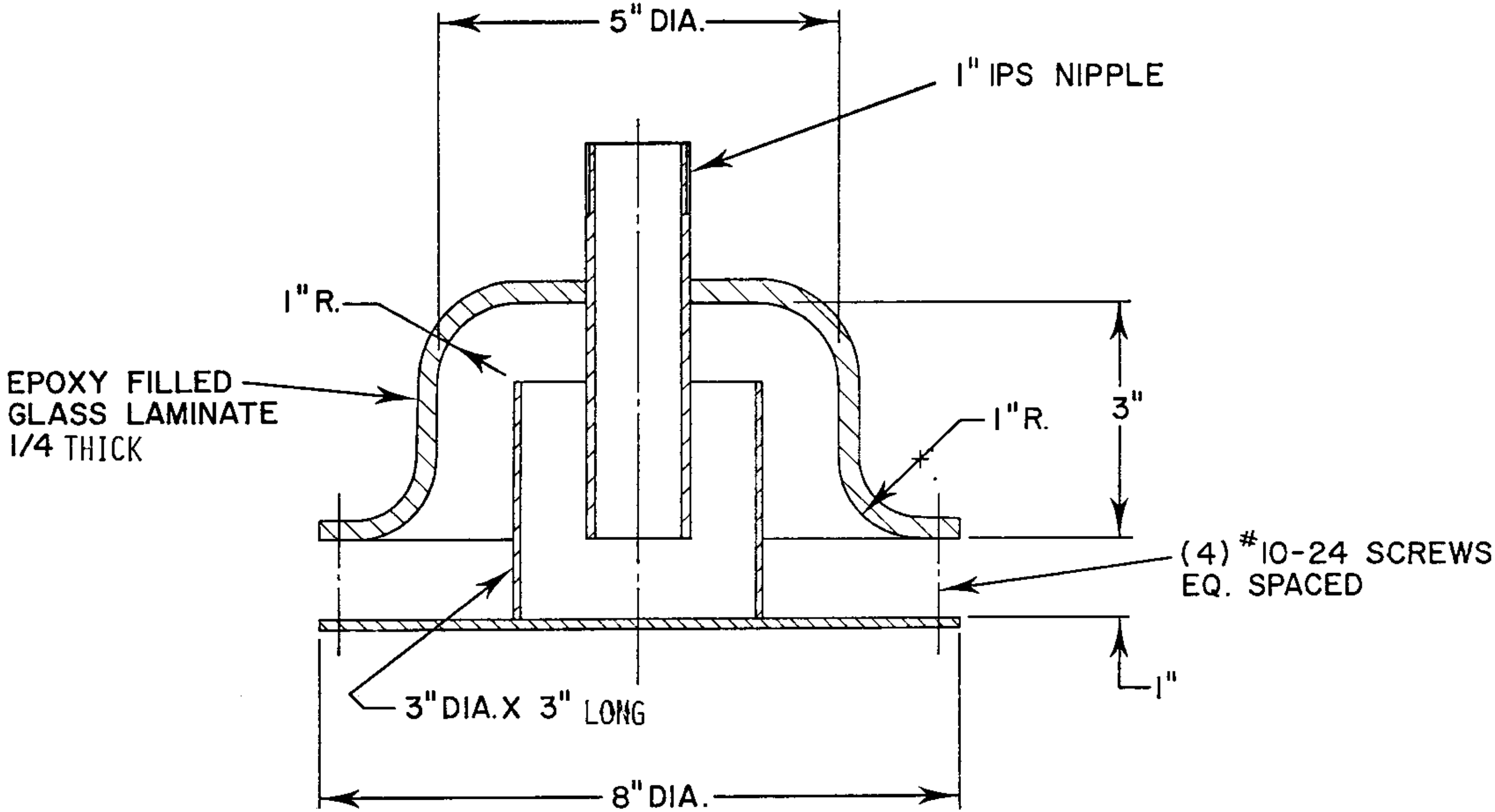
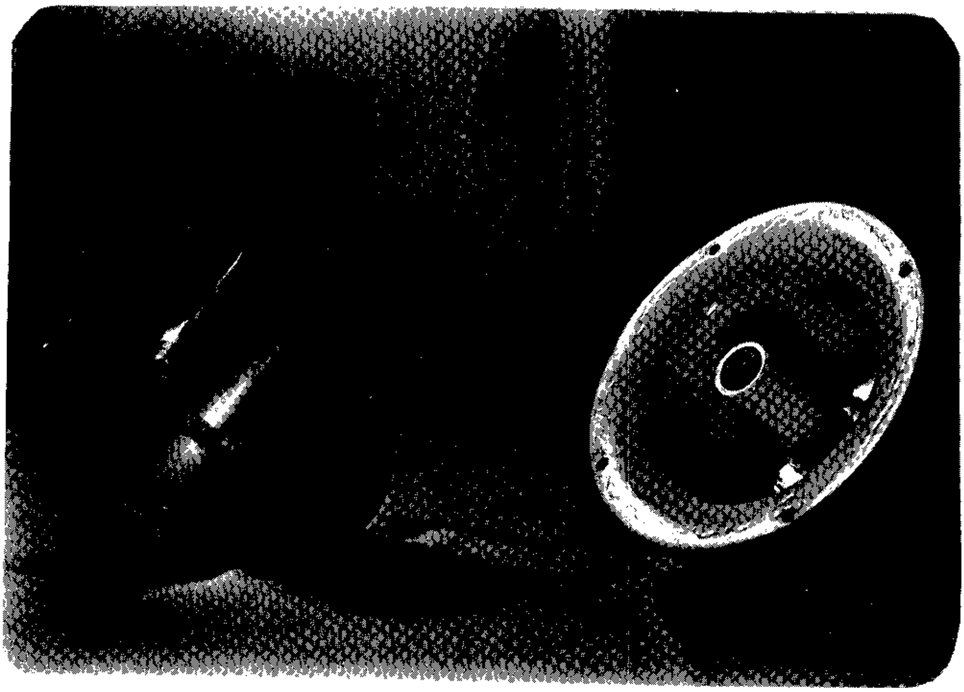
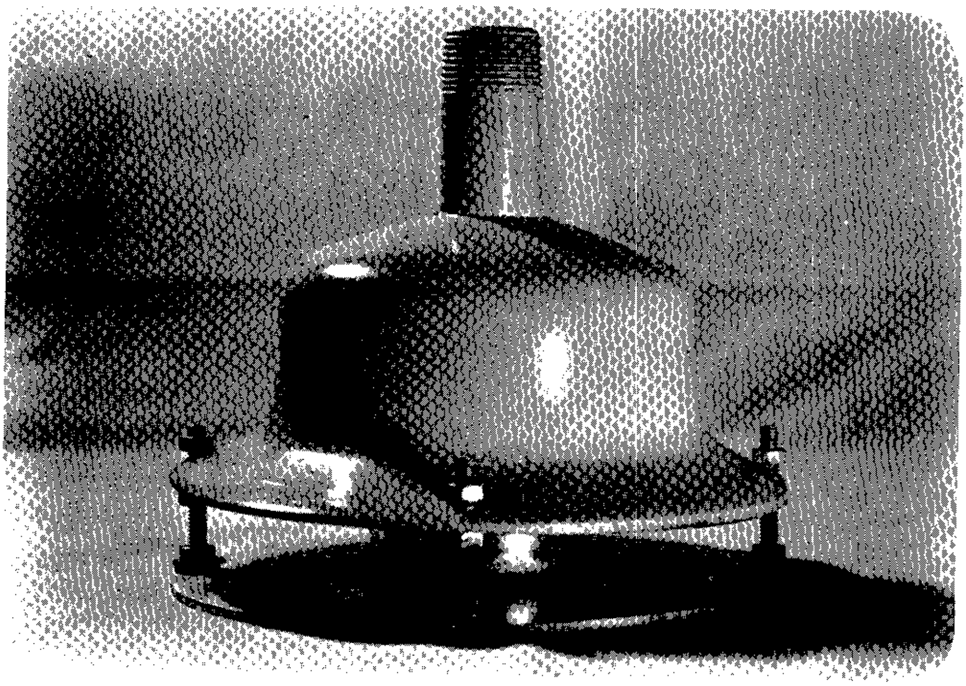


Figure 44. Plenum model fabrication sketch



a. Disassembled



b. Assembled

Figure 45. Plenum model

and discharges radially along the bottom. The scale for an 18-in. inlet pipe would require approximately a 2-ft-diameter plenum, a 6-ft-diameter diffuser body, an 8-ft-diameter discharge plane, and a 6-ft overall height. In this scale, the device would have an overall diffusion ratio of approximately 24:1, which would provide a discharge velocity of 0.75 fps for an 18-fps inlet velocity. The unit is intended to rest on or near the bottom.

Diffuser

176. Whereas the plenum discharge forces the diffusion of the flow and in the process generates turbulence, the diffuser (Figure 46) causes a gradual divergence of the flow passage that decelerates the flow to an acceptable velocity level. Figures 47a and b show the model as built and tested. In the diffuser, the slurry flow enters the unit at the top and expands through the 15-deg conical diffuser section. The 15-deg angle represents the maximum expansion ratio allowable without creating separation and causing the core flow to jet. This angle may be increased and the unit correspondingly shortened by using conical guide vanes to force a prescribed percentage of inlet flow to occupy the same percentage of annular exit area. These modifications complicate an otherwise simple design and hence would not be incorporated unless necessary. As the flow reaches the end of the diffuser section, it is turned radially outward and exits across the cylindrical discharge plane. The configuration shown is capable of reducing an 18-fps inlet velocity to 2 fps at the end of the conical diffuser and further to 0.075 fps as it exits radially from the turning section.

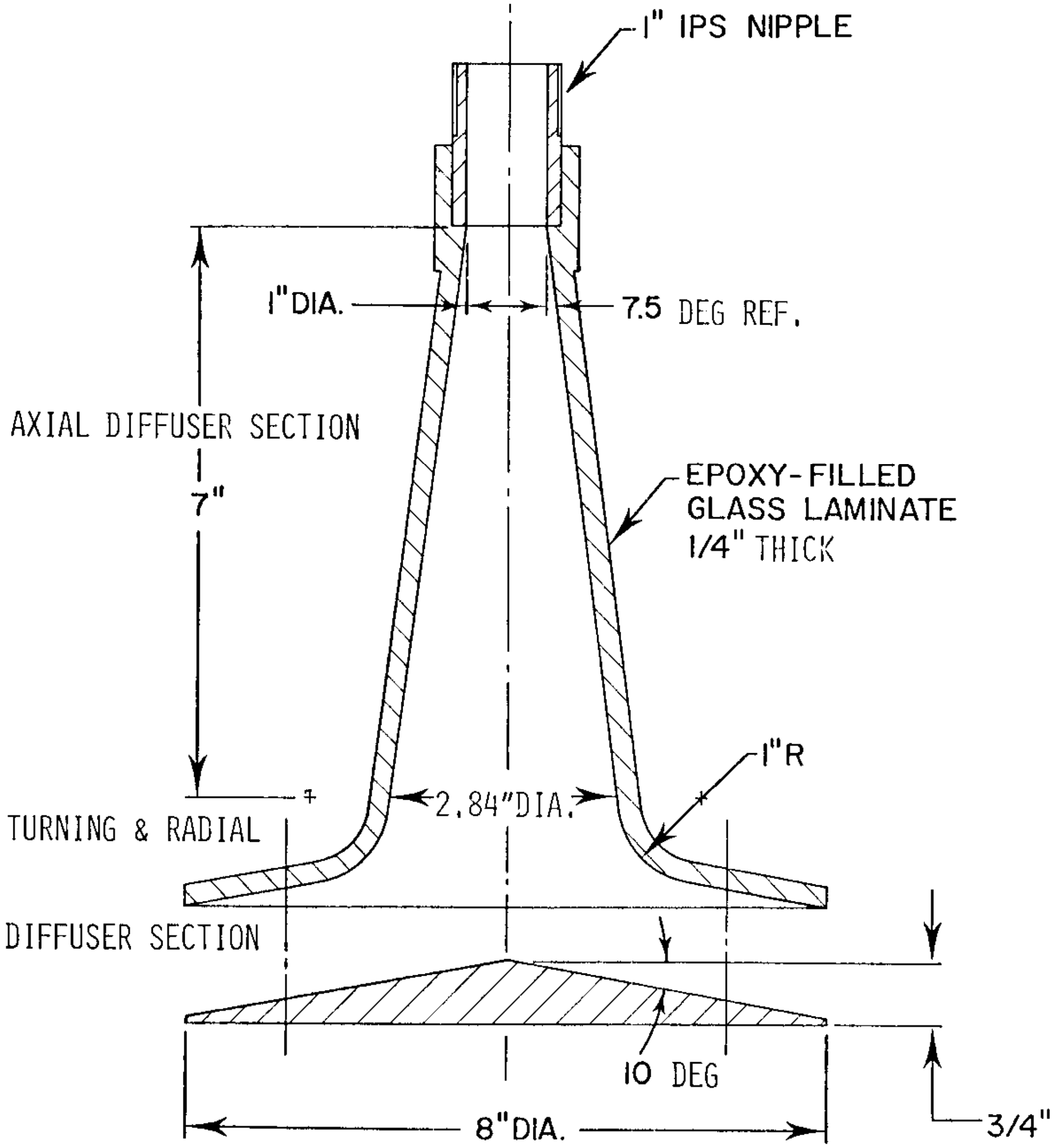
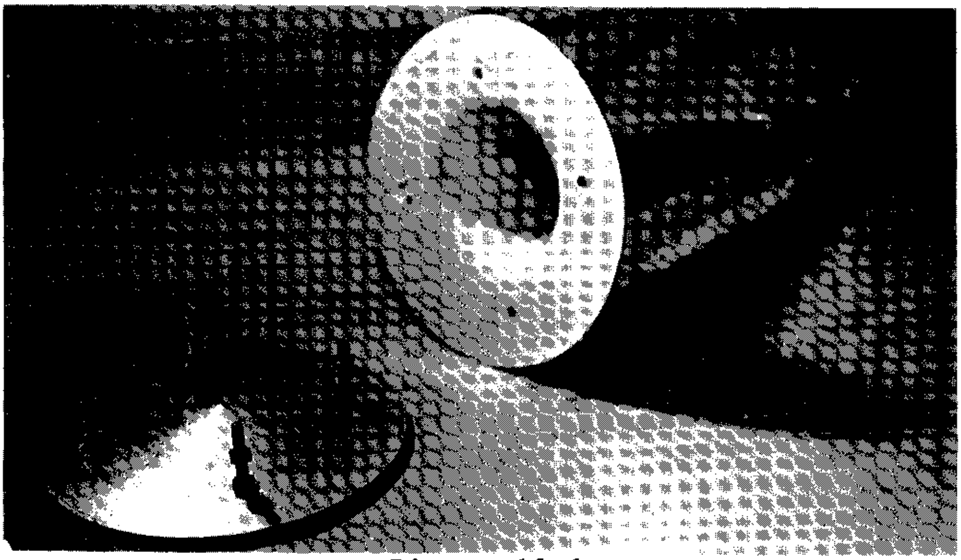
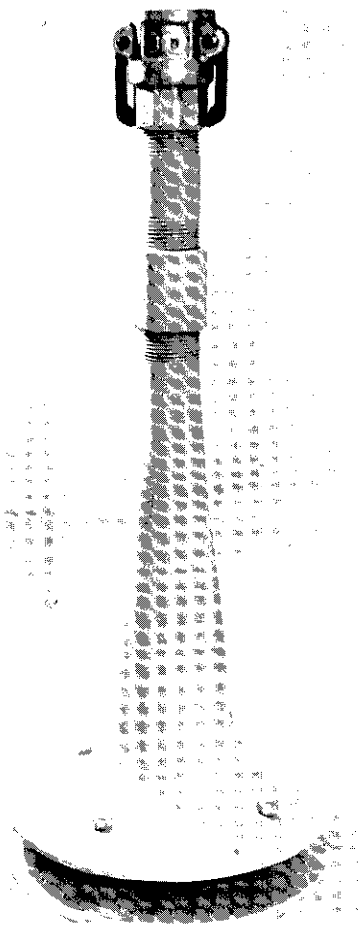


Figure 46. Diffuser model fabrication sketch



a. Disassembled



b. Assembled

Figure 47. Diffuser model

Processor Tests

Test Matrix

177. The test conditions and variations about the reference conditions for the processor program were similar to the baseline program in order to establish a basis for comparison. The reference conditions for the processor tests were as follows:

Pipe Size, ips	1 in.
Discharge height above bottom	2 in.
Pipeline velocity	4 fps
Discharge flow rate	11 gpm
Dredged material:	
Source	Boston Harbor
Type	Salt water clayey silt
Discharge solids ratio	16-18 pcs by wieght
Bottom type	Smooth
Water:	
Type	Fresh
Depth	2 ft

178. As in the baseline program, most of the variables were tested independently using a limited number of values of each variable on either side of the reference value. The one exception to this procedure was test 55 in which both pipeline velocity and height above bottom were different from the reference value. The variables and their values used

in the processor tests are illustrated by the matrix, Table 6. In additon, all of the tests that were performed, the test conditions, and the principal results are summarized in Table 7.

Test Results

179. Two of the devices, the shroud and the weir, were eliminated from further consideration after being tested only once at the reference conditions. The plenum device was tested 6 times under various conditions, and the diffuser was subjected to a total of 14 tests, the only device with which the full matrix of tests was performed.

180. The shroud was adversely affected by the reduced pressure of the slurry jet. Because of the velocity of the jet, the static pressure inside the shroud dropped below ambient; and as a result, the fabric was drawn inward and tended to fold. In addition, there was a tendency for the shroud to oscillate. For these reasons and because the full-scale shroud would be awkward to handle, especially in currents, it was decided to eliminate the shroud.

181. The weir was readily eliminated because of poor performance Instead of the weir dissipating sufficient energy inside the dish to allow it to fill and overflow, the energy of the discharge stream created a persisting vortex which generated turbidity in the water column to a considerable height.

182. From the standpoint of reducing turbidity and controlling the mud flow, the plenum and diffuser processors were both effective and performed about equally. This fact was well established by the time six runs had been performed with the plenum. At that point, it was decided

Table 6

Matrix for the Processor Test Program

	Water Type	Sediment Type	Bottom Type	Slurry Concentration	Pipe Flow Velocity fps	Height Above Bottom
		Silty Clay		High	6	Zero
Reference Conditions	Fresh	Clayey	Smooth	Medium	4	Low
		Silt				
	Salt	Silty Sand		Low	2	High

Table 7

Processor Test Conditions and Results

Test Number	Water Type	Sediment Type	Slurry Concentration pcs	Discharge Velocity fps	Discharge Height Above Bottom, in.	Processor Type	Cloud Height in.	Mud Flow Height in.	Head Wave Velocity fps
34	Fresh	Clayey Silt	22.4	4	2-1/2	Shroud	3-1/4	2	0.197
35			22.2		On bottom	Plenum	1-1/4	1	0.030
38			16.8		2		3	1-3/4	0.085
43			15.3		4		3-1/2	1-3/4	0.144
48			19.0		2		2	1-1/4	0.075
54	Salt 26^{o}/oo		20.3				1-1/2	*	0.069
37	Fresh		13.7		On bottom	Weir	5	3-1/2	0.201
39			17.9		On bottom	Diffuser	1	1	0.058
40					2		3	1-3/4	0.089
41			16.9		4		3	2-1/2	0.165
42			16.0				3	2-1/4	0.155
44			14.9	6	2		3	2-1/4	0.089
45			18.5	2			1	1	0.048
46			19.2	4		Diffuser 90 deg open	1-1/2	*	0.066
47						Diffuser	2	1-1/2	0.096
49			9.8				3	1-3/4	0.104
50			21.9				3	1-1/2	0.128
51		Silty Clay	18.4				3-1/4	1-3/4	0.104
52		Silty Sand	19.0				3	1-1/2	0.110
53	Salt	Clayey Silt	20.4				1-1/2	*	0.082
55	26^{o}/oo		13.6	6			3/4	*	0.027

*Test conditions precluded measurement.

Note: No entry indicates that preceding entry still aplies.

to terminate the plenum tests and to concentrate the remaining tests on completing the matrix for the diffuser. This choice was based on practical considerations and not on the test results. The diffuser is inherently less prone to blocking by accumulated solids, and in the event of blocking, could be cleaned more readily than the plenum. For these reasons, it was decided to base the design of the full-scale system on the diffuser.

183. The results of the diffuser tests are presented in Figures 48-52. For each of the independent variables, the results of the baseline tests and the processor tests are shown together for comparison. The numbers adjacent to the diffuser data points identify the test numbers.

184. The results presented are the head wave velocity, mud flow height, and cloud height, which, when compared with baseline results, serve as measures of effectiveness of the diffuser. Since the primary purpose of using a submerged discharge is to reduce turbidity, particularly that near the surface, the effect on cloud height, which is the upper extent of visible turbidity generated by the discharge, is the most direct measure of effectiveness of the diffuser. However, the mud flow height and head wave velocity, which together define the momentum of the mud flow, are also of interest because they affect the extent of the mud flow generated by the discharge.

185. Discharge Angle. In Figure 48, the baseline results are shwon for the three different discharge angles tested (horizontal, 20-deg, and vertical). Only one point is shown for the diffuser test

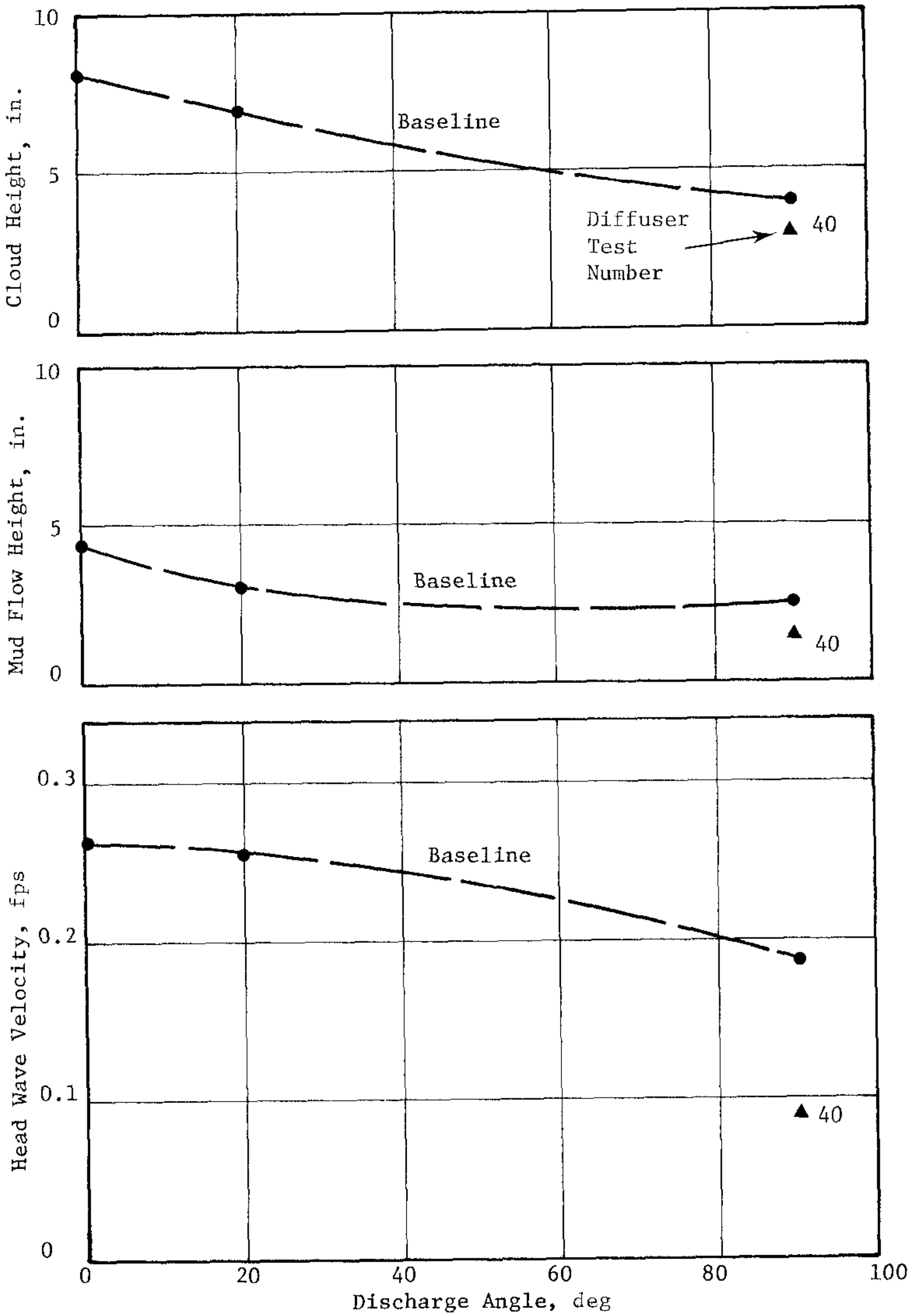


Figure 48. Diffuser results versus baseline results at various discharge angles

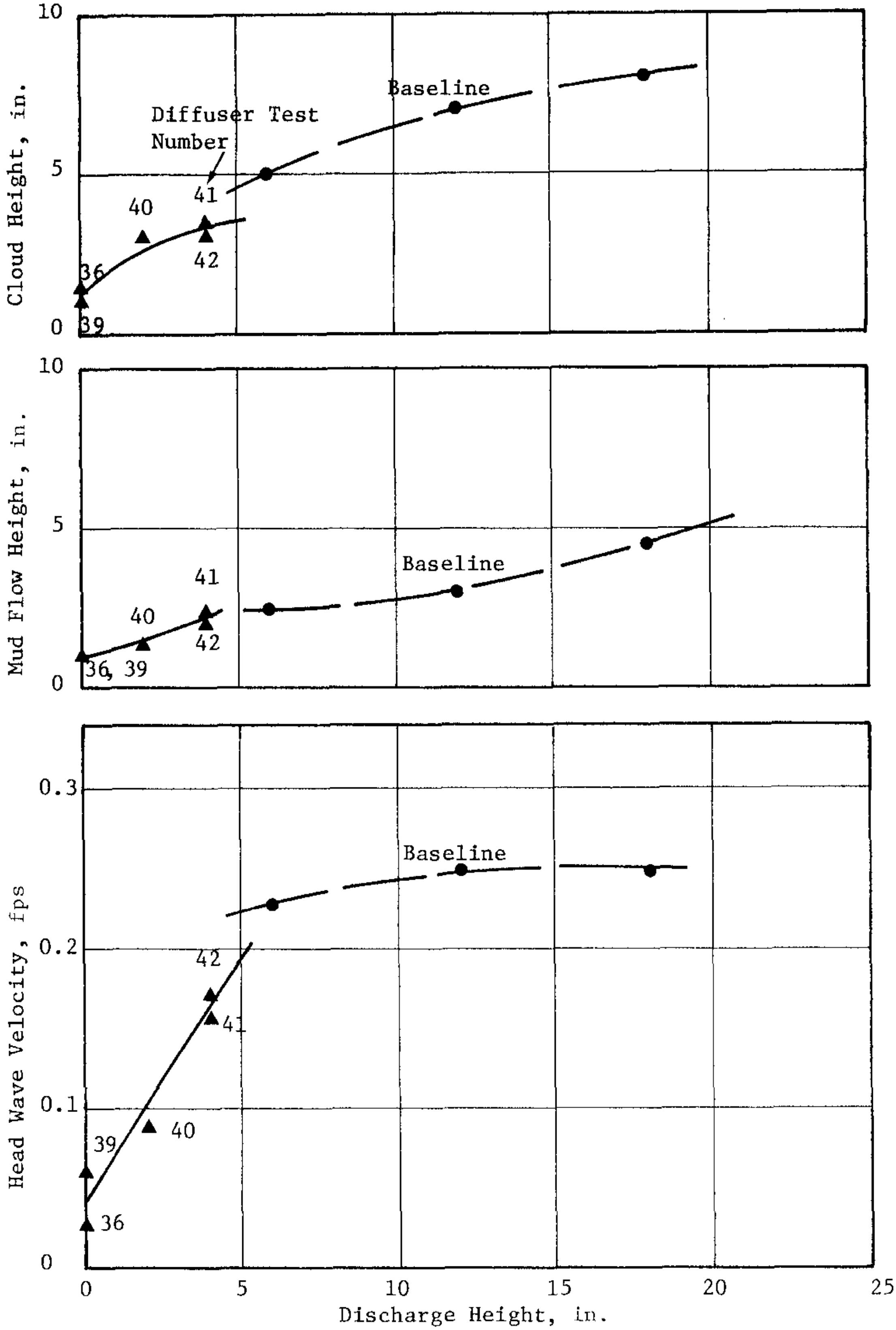


Figure 49. Diffuser results versus baseline results for various discharge heights

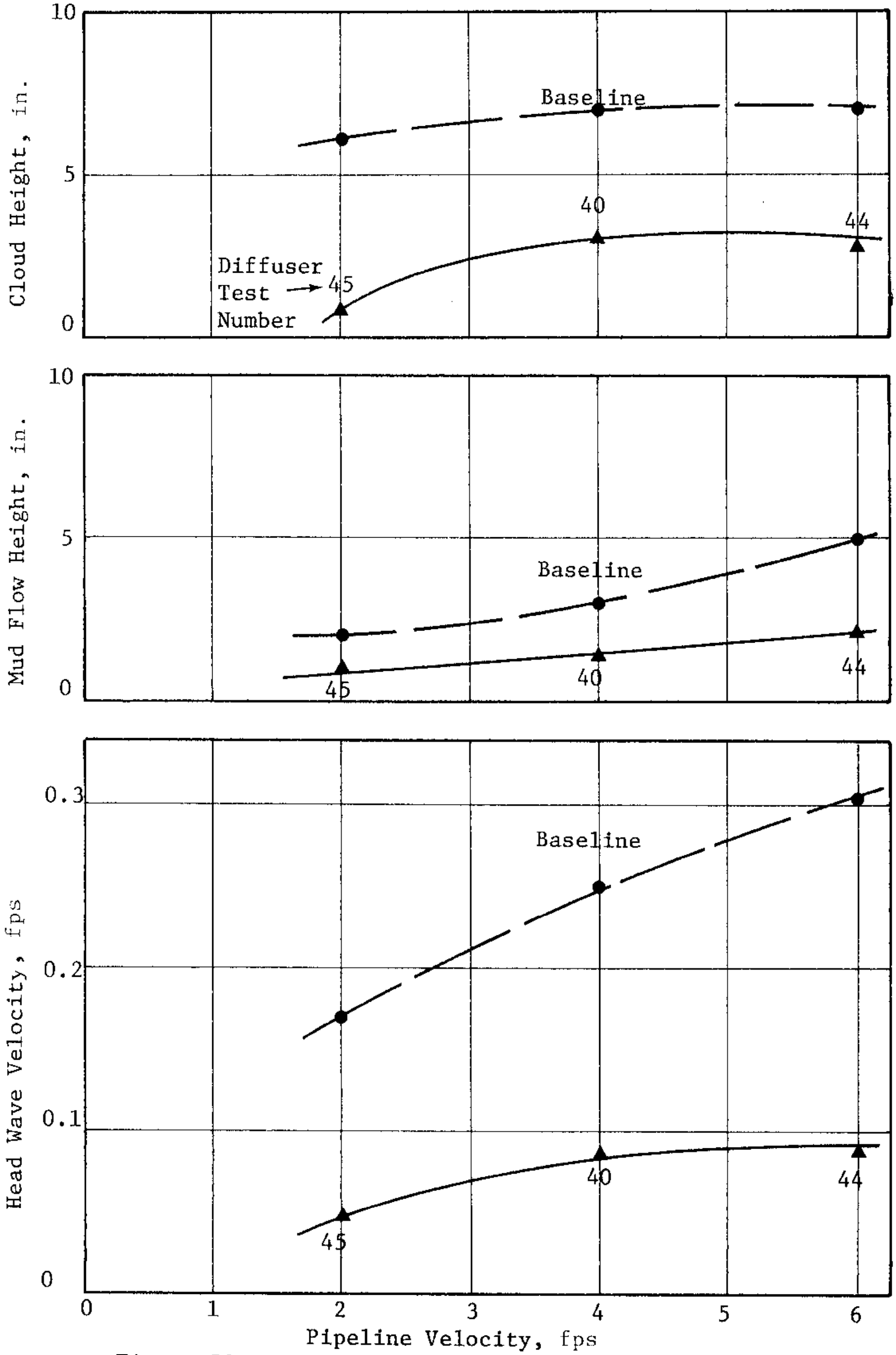


Figure 50. Diffuser results versus baseline results for various pipeline velocities

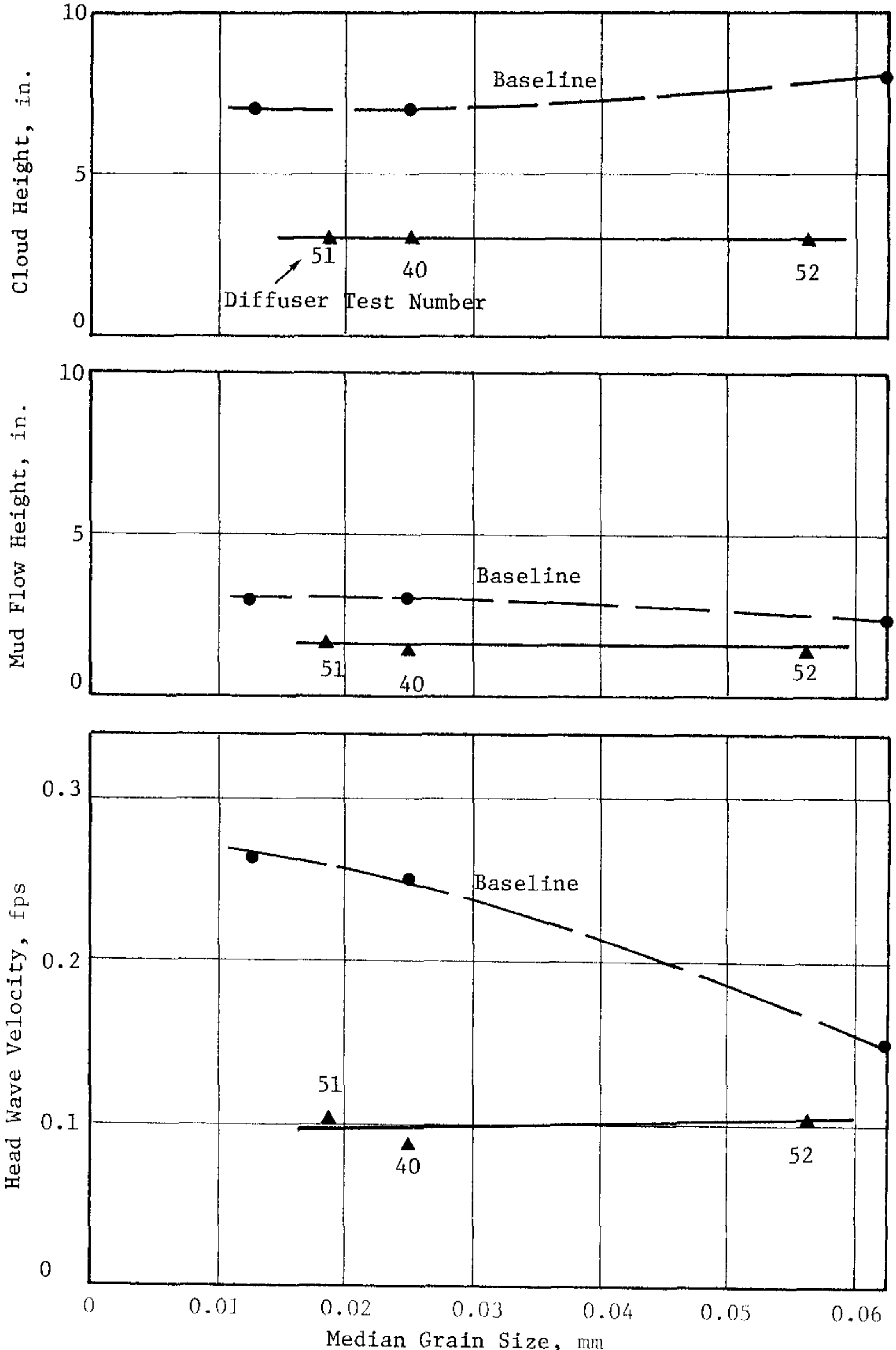


Figure 51. Diffuser results versus baseline results for various sediment types

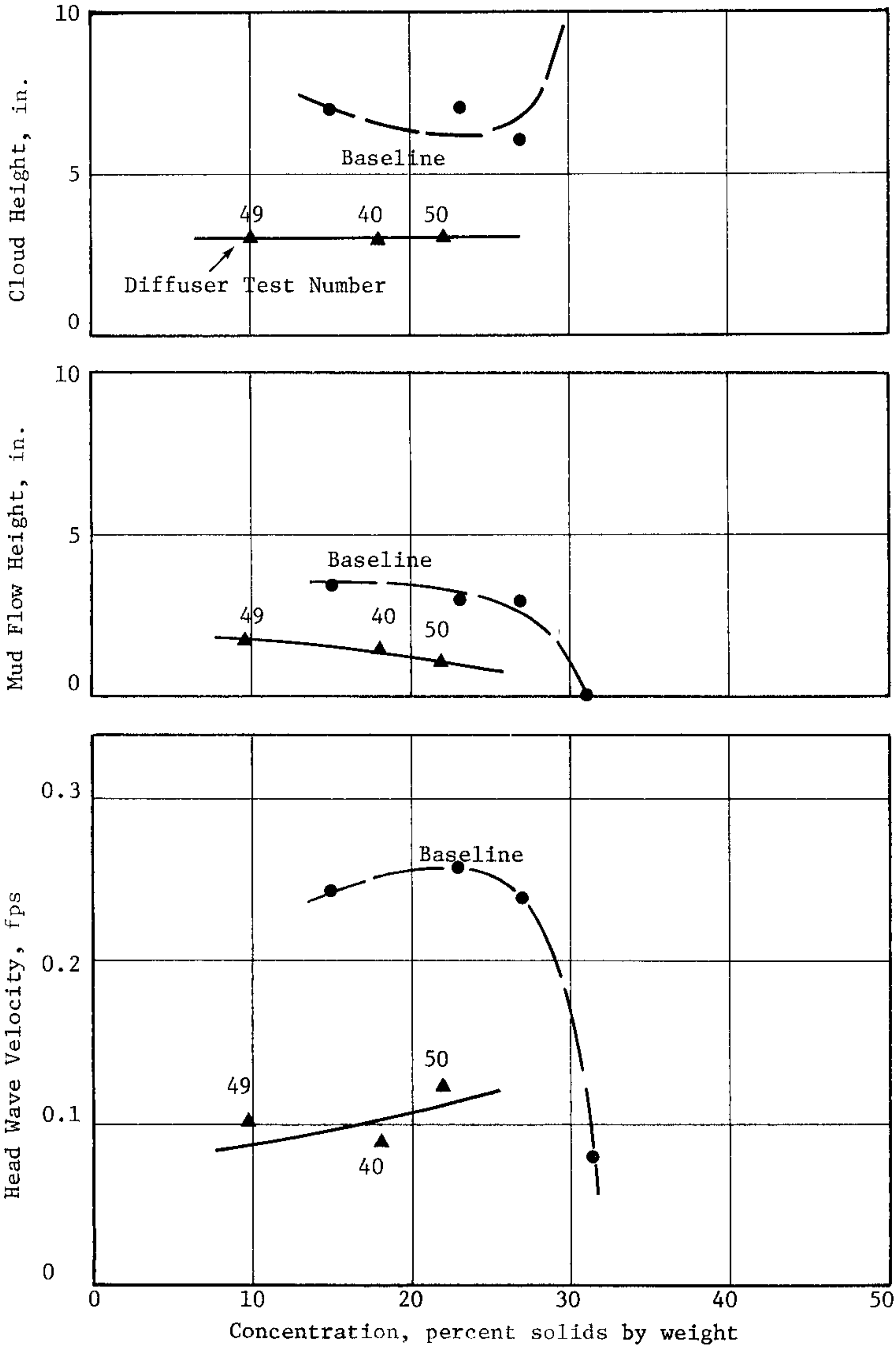


Figure 52. Diffuser results versus baseline results for various solids concentrations

because the diffuser is designed to operate in only one position: with its longitudinal axis vertical. The single point shown for the diffuser is from test 40, the reference case, in which the diffuser is elevated 2 in. above the bottom. The resulting cloud height was 3 in. compared with the 7 in. observed for the reference case in the baseline program (20-deg discharge angle). However, when the open pipe in the baseline program was oriented vertically, the cloud height was reduced to 4 in. outside the immediate vicinity of the discharge. This shows that a simple open pipe, submerged and arranged to discharge straight down, is a fairly effective way of reducing turbidity if other effects such as bottom scouring are not a concern. On the other hand, the diffuser still decreases significantly the mud flow height and head wave velocity of the baseline case with a vertical discharge. Thus, the diffuser's performance is superior in controlling both turbidity and the mud flow momentum.

186. Discharge Height. Figure 49 illustrates the effect of discharge height above bottom. The diffuser, which is designed to be positioned close to the bottom, is quite effective compared with the open pipe at a 20 deg angle when the two are operating at what could be considered their respective normal heights. However, as the two heights approach each other, the performance of the open pipe appears to approach that of the diffuser for cloud and mud flow heights. It seems highly unlikely, however, that the performance of the open pipe with its high momentum discharge could be extrapolated back to zero height and obtain results comparable to the diffuser.

187. Pipeline Velocity. The comparison between the baseline test results and the diffuser results for various pipeline velocities (Figure 50) shows most distinctly the effect of the diffuser in reducing the momentum of the discharge stream. All three mud flow parameters are significantly reduced by the diffuser.

188. Sediment Type. Figure 51 shows the results for three different sediment types: silty clay, clayey silt, and silty sand. Because of some difficulty encountered in controlling clay and sand contents, the diffuser tests were not made at exactly the same median grain size as those of the baseline tests. In all cases, the diffuser reduced the mud flow characteristics considerably below the baseline results. In addition, the cloud and mud flow heights appear to be relatively insensitive to median grain size for both the open pipe and the diffuser. Yet in all cases the diffuser yields lower cloud and mud flow heights.

189. In the case of the baseline configuration, however, the head wave velocity drops significantly with increased median grain size while the diffuser shows no significant effect. Since the sand content was somewhat lower for the diffuser test, the difference could be attributed in part to that fact. However, as the sand content increases, resulting in increased settling, the amount of material remaining in suspension should be lower with a corresponding decrease in the density difference, which drives the mud flow.

190. Concentration. The influence of slurry concentration for the diffuser and the baseline runs is compared in Figure 52. Again, the diffuser tests reflect a considerable reduction in the mud flow

parameters. One of the baseline runs, in which the concentration was 31 percent, reflects essentially no mud flow and much of the slurry was simply deposited on the bottom as agglomerated lumps. No comparable run was made with the diffuser because 31 percent is an unrealistically high average solids concentration for normal dredging situations.

CHAPTER VI: FULL-SCALE PREDICTIONS

191. In Chapter IV, the rationale for using the Froude numbers as a basis for establishing the scale of the submerged discharge experiments was developed. In that same chapter the experimental results from the baseline test were presented, and several data correlations were examined. They also indicated that the Froude number appears to be a valid basis for scaling.

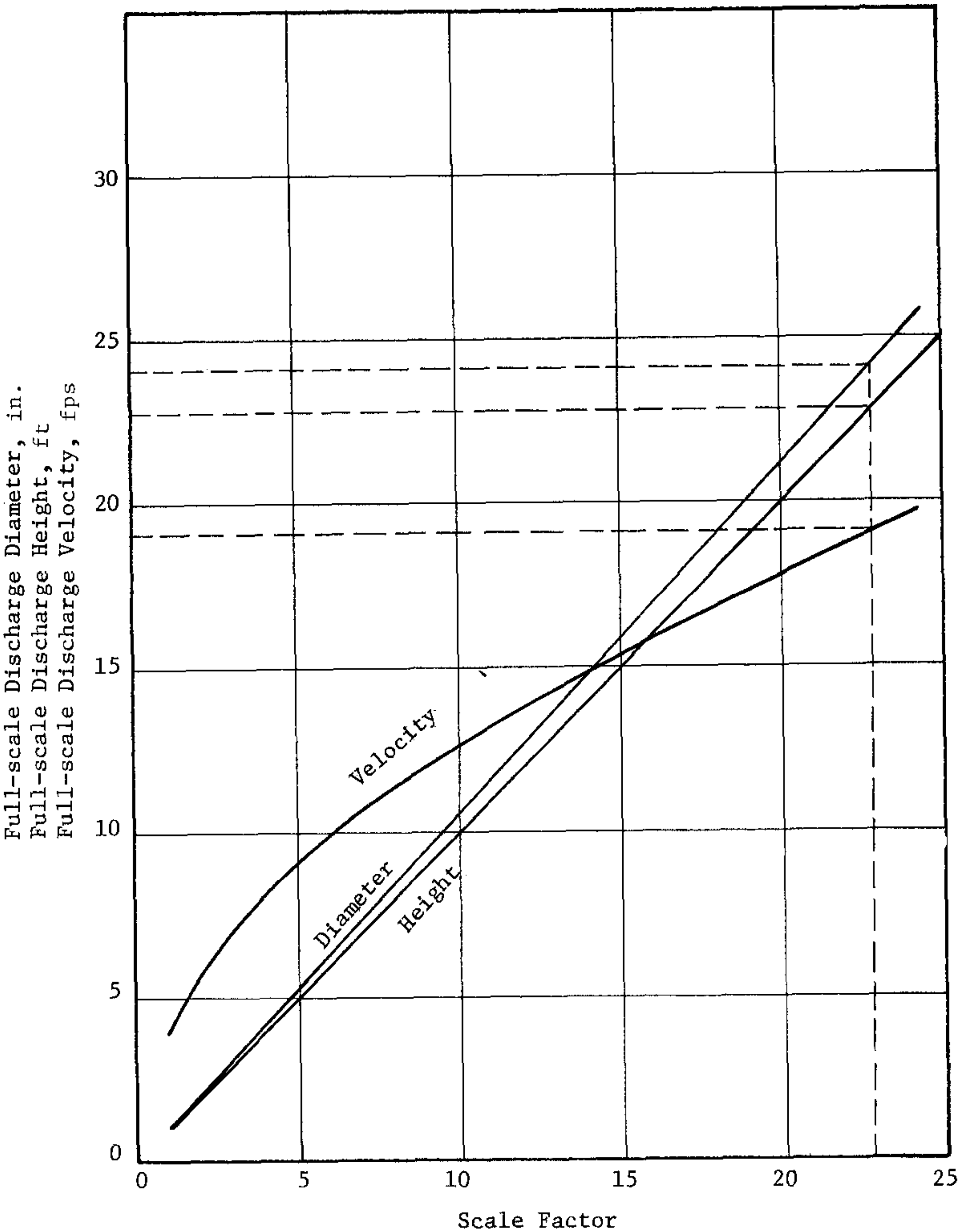
192. Predictions of full-scale mud flow parameters can be made by scaling the experimental results up to a full-scale dredging arrangement. For such predictions to be correct, the full-scale conditions must be geometrically similar to the experimental conditions and must be characterized by the same Froude number. Geometric similarity, for example, requires that the ratio of pipe diameter to discharge height above bottom be the same in full scale as in the experimental configuration.

193. One of the test conditions that will not be duplicated in the field is the confinement of the mud flow by the walls of the test tank. For exact geometric similarity the dredged material would have to be confined by a trench whose width is the width of the test tank (4 ft) times the scale factor (typically 20). That is, the confining trench would typically be about 80 ft wide. Clearly, this is a completely unlikely circumstance; however, a logical basis for useful full-scale predictions can be established.

194. In practice, it is probably common for the mud flow created by a typical hydraulic dredge discharge to flow away from the discharge

area in a stream whose width is dictated by the bottom slope, bottom contours, initial direction of the discharge stream, subsurface currents, and perhaps other influences. In the test tank the walls in the neighborhood of the discharge pipe reflect the lateral motion of the head wave and generally redirect the mud flow parallel to the walls either in the forward or rearward direction. This motion is established in approximately two tank widths downstream from the discharge point. Beyond this distance the parallel walls maintain a two-dimensional flow and specifically prevent the head wave and mud flow from expanding sideways, slowing down, and becoming less thick. Since real mud flows are generally not this confined (particularly a radial mud flow from a vertical discharge pipe), predictions based on tank data produce somewhat excessive values of mud flow properties. Therefore, predicted values of cloud height, mud flow thickness, and head wave velocity can be considered as upper limits that are not likely to be exceeded in real situations.

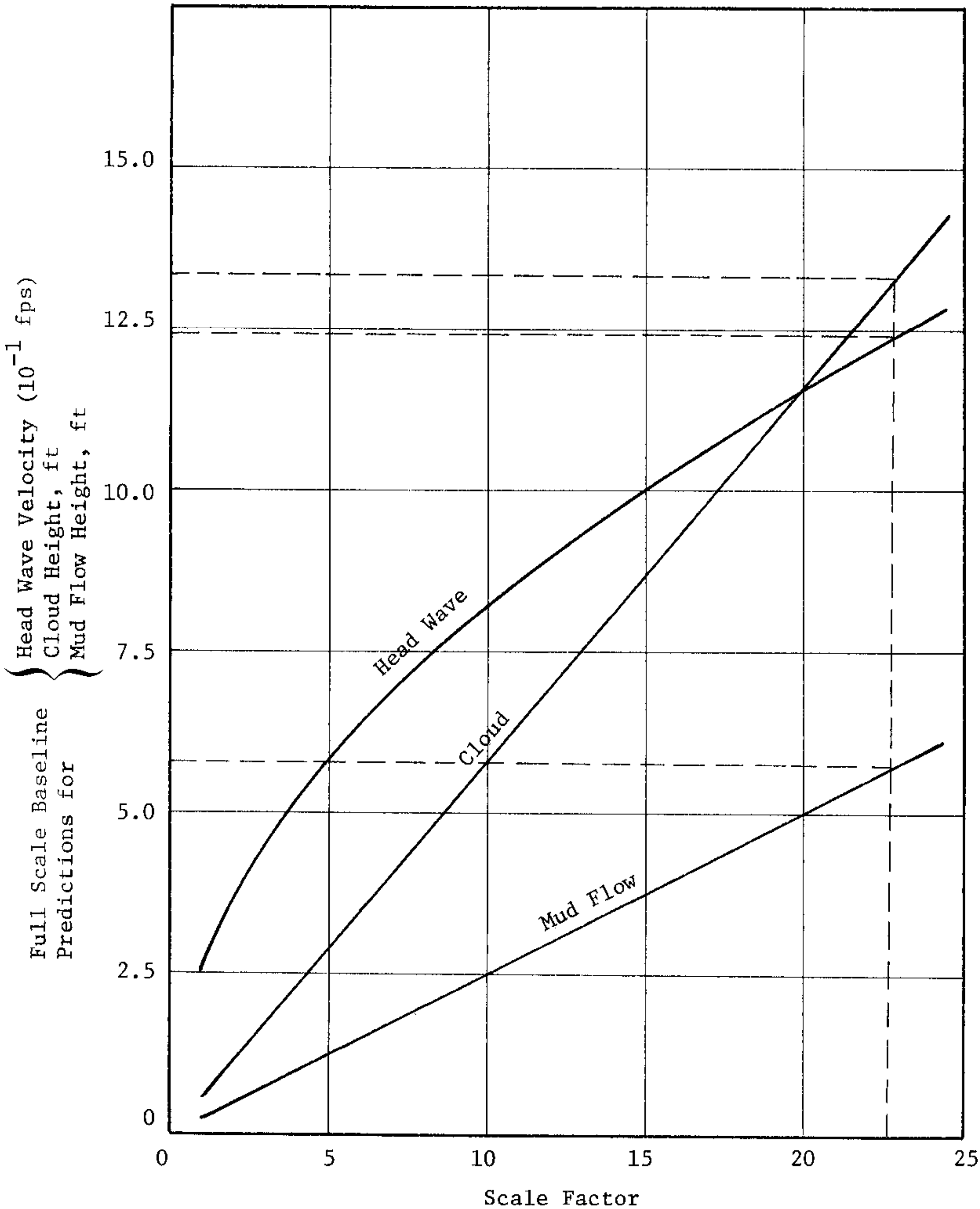
195. A method has been developed for predicting full-scale mud flow parameters which involves the use of five sets of curves (Figures 53-57) and six computational steps. The method scales up the parameters of the baseline configuration (test 11, Table 3) according to constant Froude numbers and then applies correction factors for those properties that do not match the example. Figure 53 presents the full scale values of the independent parameters as a function of scale factor. The tank scale parameter values are noted on the figures. The full scale values of the dependent variables are presented in Figure 54 also as a function of scale factor. If the discharge height and discharge velocity of the example do not conform to the scaled up values for the



Discharge Angle = 20 deg
Discharge Height = 12 in.
Discharge Pipe Diameter = 1.049 in. ips ID

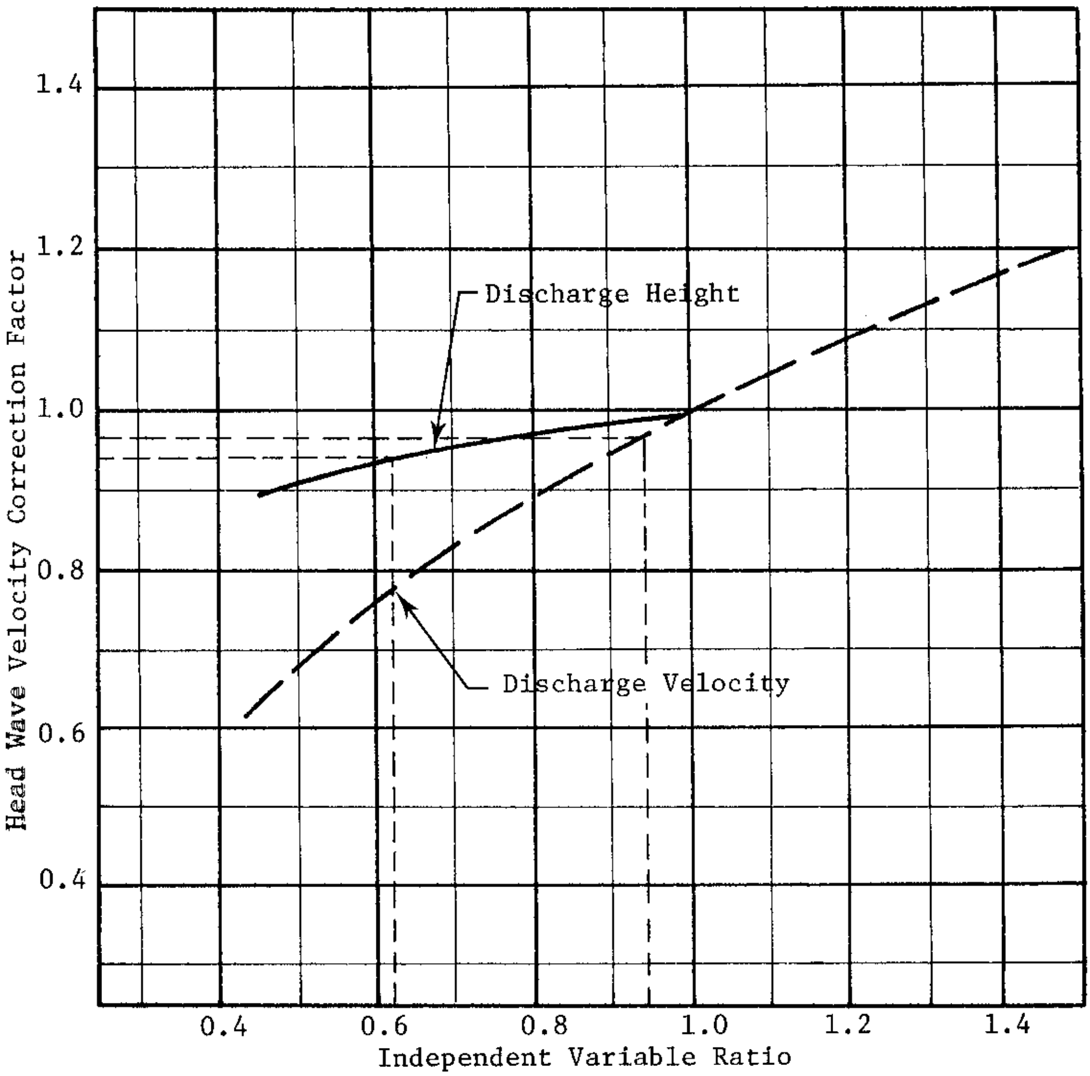
Discharge Velocity = 4 fps
Sediment = Clayey silt
Concentration = 23 percent solids by weight

Figure 53. Full-scale discharge parameters for various scale factors



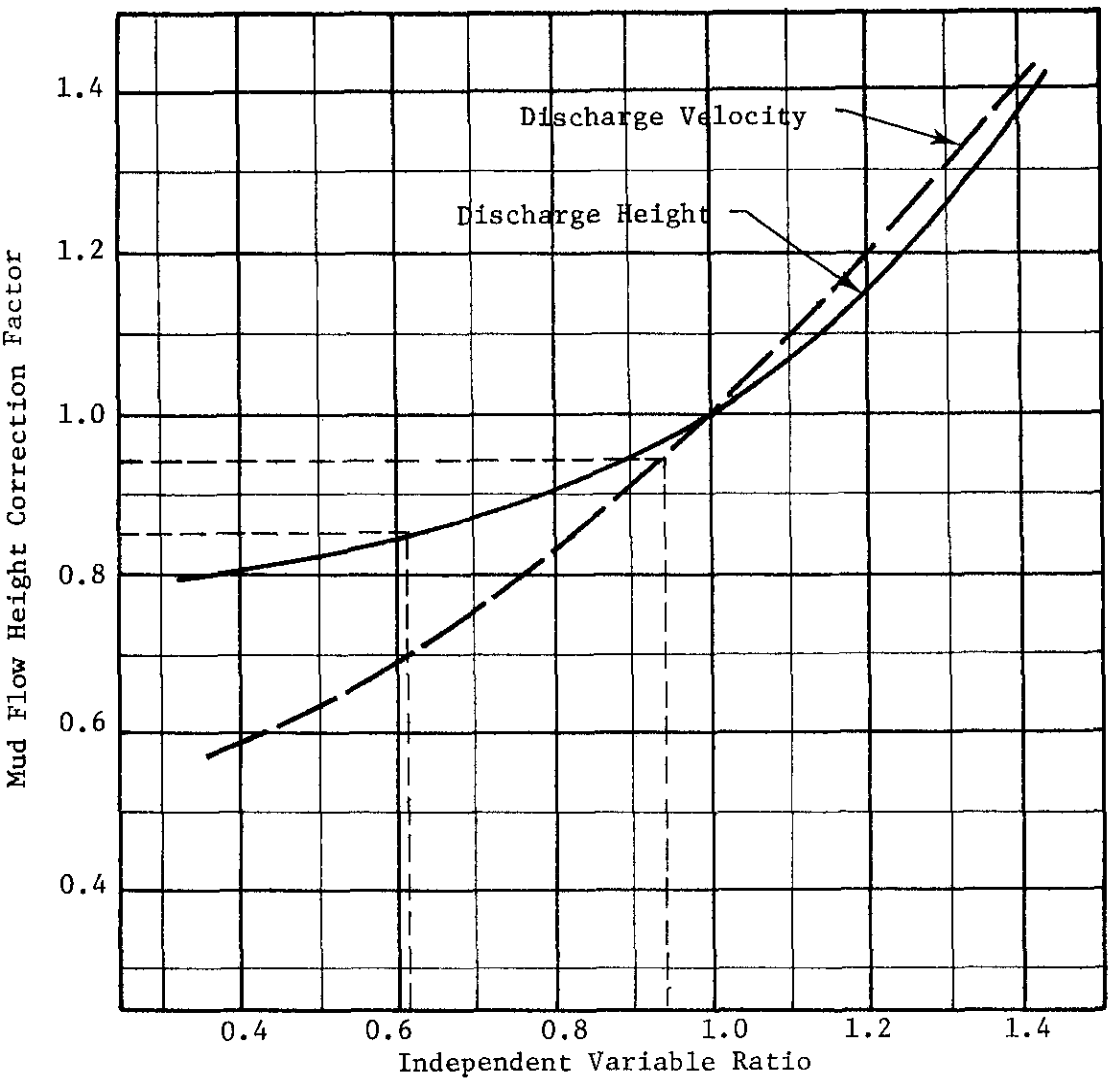
Discharge Angle = 20 deg Discharge Velocity = 4 fps
Discharge Height = 12 in. Sediment = Clayey silt
Discharge Pipe Diameter = 1.049 in. ips ID Concentration = 23 percent solids by weight

Figure 54. Full-scale baseline predictions



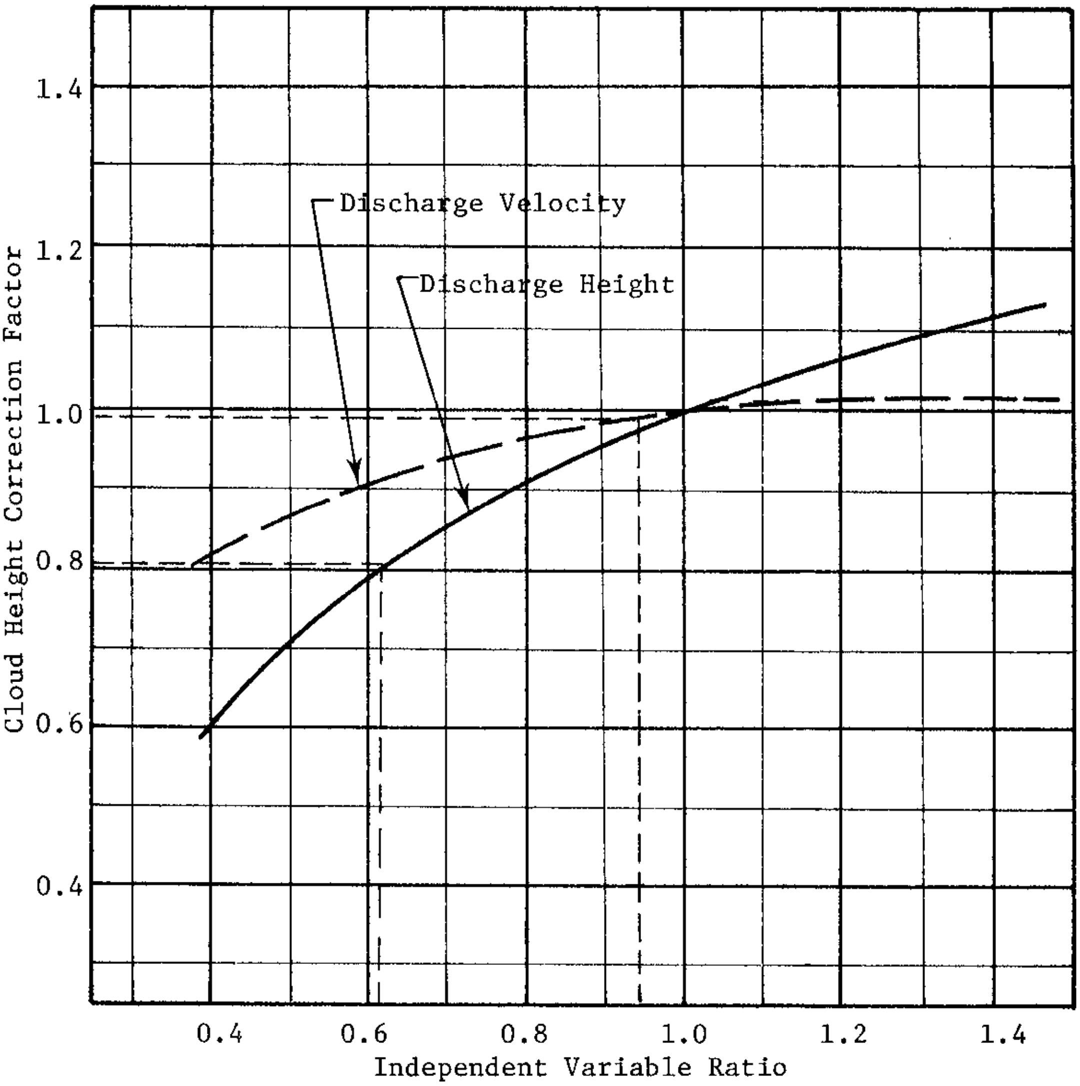
Discharge Angle = 20 deg
Sediment = Clayey silt
Concentration = 23 percent solids by weight

Figure 55. Head wave velocity corrections for off-reference conditions



Discharge Angle = 20 deg
Sediment = Clayey silt
Concentration = 23 percent solids by weight

Figure 56. Mud flow height corrections for off-reference conditions



Discharge Angle = 20 deg
Sediment = Clayey silt
Concentration = 23 percent solids by weight

Figure 57. Cloud height corrections for off-reference conditions

baseline case, the dependent variable values (head wave velocity, mud flow and cloud heights) must be corrected accordingly. The head wave velocity corrections are shown in Figure 55 for off-reference discharge height and discharge velocity conditions. The curve labeled Discharge Velocity was developed from the head wave velocity data shown in Figure 29. The discharge velocity values on the abscissa were ratioed to the baseline value (4 fps) and the head wave velocity data on the ordinate were ratioed to the value measured in the baseline test (0.257 fps). Therefore, the non-dimensional trends of the tank scale data for the baseline configuration were used to correct for off-reference conditions at full scale. The same procedure and the data from Figure 27 were used to develop the discharge height correction curve in Figure 55. The mud flow height correction curves and the cloud height correction curves were developed in the same manner from the data of Table 3, test 11, Figures 27 and 29, and are presented in Figures 56 and 57 respectively.

196. The prediction method can be best demonstrated by an illustrative example. It is desired to predict the cloud height, mud flow height, and head wave velocity for the following discharge configuration:

- a. Submerged discharge pipe oriented at 20 deg downward
- b. 24-in. discharge diameter
- c. 18-fps discharge velocity
- d. Discharge height 14 ft above bottom

Step 1: Determine Scale Factor

197. The scale factor is the ratio of the full-scale pipe diameter to that of the pipe in the test facility:

$$\text{Scale factor} = \frac{24}{1.049} = 22.9$$

where the diameter of 1.049 in. for the test condition is the actual diameter of the 1-in.-ips pipe used for the reference conditions in the baseline tests.

Step 2: Determine full-scale reference conditions

198. Using the scale factor determined in Step 1, enter the curve in Figure 53 to determine operating conditions for a full-scale reference configuration that is geometrically similar to the baseline reference test:

Discharge diameter	=	24 in.
Discharge velocity	=	19.1 fps
Discharge height	=	22.9 ft

Step 3: Determine predictions for the full-scale reference conditions

199. Again using the scale factor, enter the curve in Figure 54 to determine predictions for the full-scale reference conditions:

Head wave velocity	=	1.23 fps
Mud flow height	=	5.72 ft
Cloud height	=	13.3 ft

Step 4: Determine ratios required to obtain correction factors

200. Since these predictions are for a full-scale reference condition in which the discharge velocity and discharge height above the bottom differ from those in the example, it is necessary to obtain correction factors that will be used to modify the reference prediction

to agree with the example. The first step in obtaining the correction factors is to form ratios of desired discharge velocity to the reference discharge velocity and the desired height to the reference height above bottom:

$$\text{Discharge velocity ratio} = \frac{18}{19.1} = 0.94$$

$$\text{Height above bottom ratio} = \frac{14}{22.9} = 0.61$$

Step 5: Obtain correction factors

201. Since predictions are to be made for three parameters (cloud height, mud flow height, and head wave velocity), and correction factors are required for two off-reference conditions (discharge velocity and height above bottom), a total of six correction factors are required. These are obtained by entering the curves of Figures 55, 56, and 57 for head wave velocity, mud flow height, and cloud height, respectively. The correction factors are as follows:

Parameter	Discharge Velocity Correction	Discharge Height Above Bottom Correction
Head wave velocity	0.97	0.94
Mud flow height	0.95	0.85
Cloud height	0.99	0.80

Step 6: Apply correction factors

202. To obtain the predicted values which apply to the conditions of the original example, each reference condition prediction is multiplied by the two correction factors obtained in Step 5.

Head wave velocity prediction = 1.23 x 0.97 x 0.94 = 1.12 fps

Mud flow height = 5.72 x 0.95 x 0.85 = 4.62 ft

Cloud height = 13.3 x 0.99 x 0.80 = 10.5 ft

203. The correction factor curves used in this example were developed from test data obtained in the baseline tests in which the independent variables were varied singly. Hence the predictions are based on an inherent assumption that there are no interactive influences. Furthermore, the range of full-scale conditions for which predictions can be made is necessarily limited by the range of the variables actually tested. In particular the predictions should be applicable for a distance of 24 x scale factor ft from the discharge point.

204. Predictions can also be made for head wave velocity, cloud height, and mud flow height for the case of operations with the full-scale diffuser. As an example, Figure 58 shows the scaled-up predictions for the reference case (test 40). These curves are valid for the full-scale situation in which the Froude number and geometric relationships are held the same as for the reference case. Figures 59, 60, and 61 provide correction factors for a limited range of off-reference conditions as derived from the data of Figures 49 and 50. The procedure for developing the full-scale prediction for the diffuser is the same as that outlined for the submerged pipe configuration.

205. For purposes of illustration and comparison, consider a diffuser for the dredging operation of the preceding submerged pipe example. The pipeline diameter is 24 in. and the dredged material slurry moves at 18 fps through the discharge pipe. The diffuser is

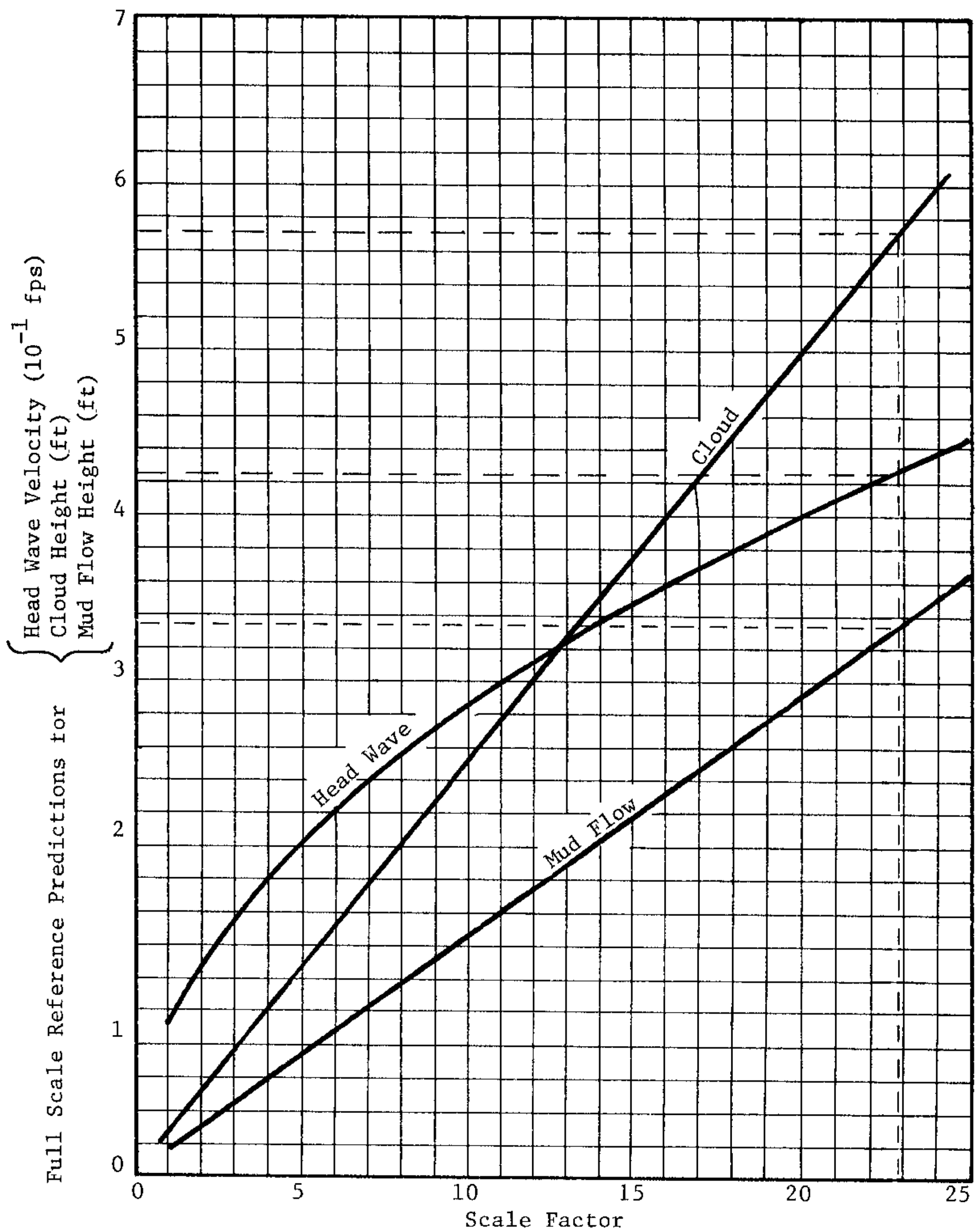
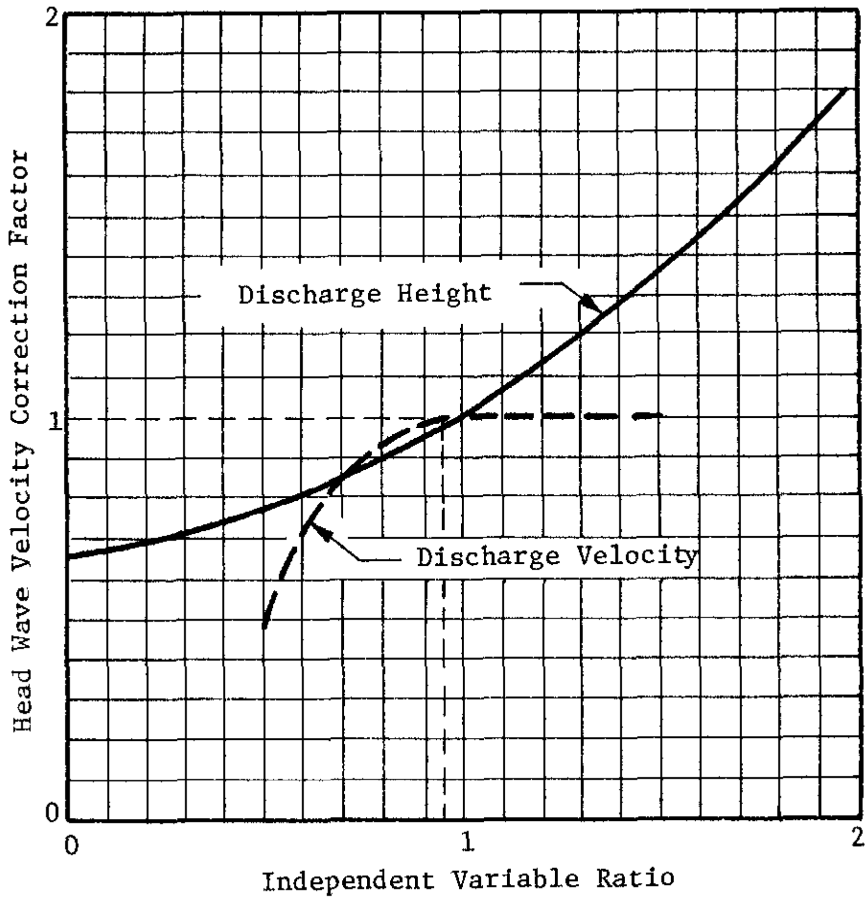
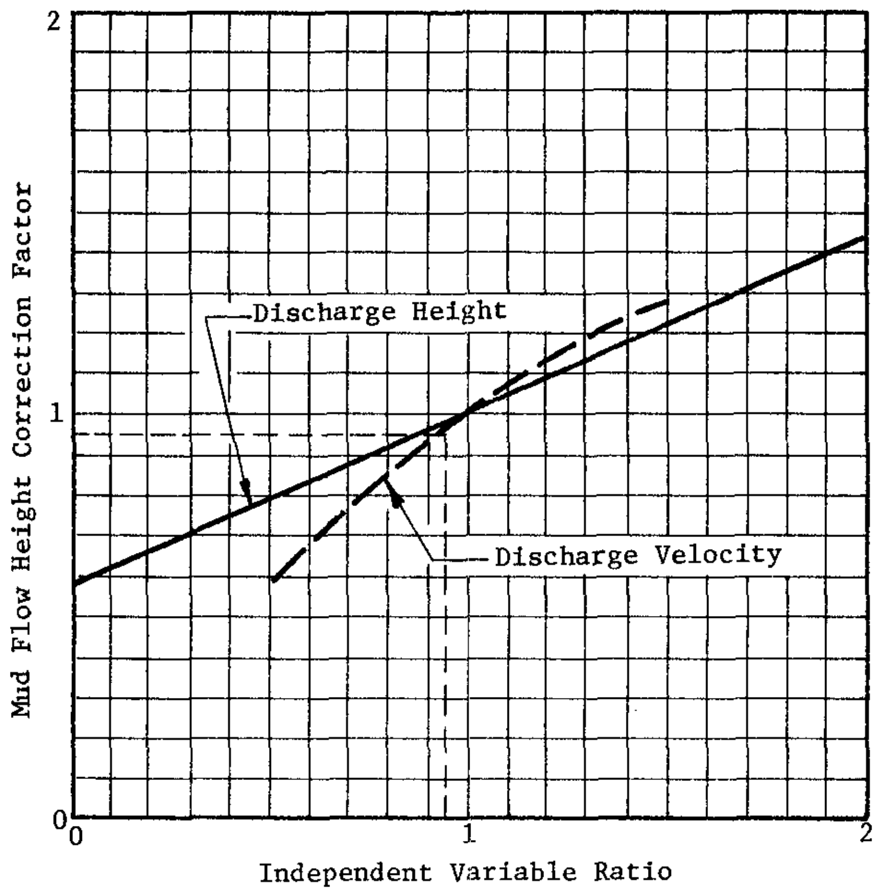


Figure 58. Full-scale predictions for operations with diffuser



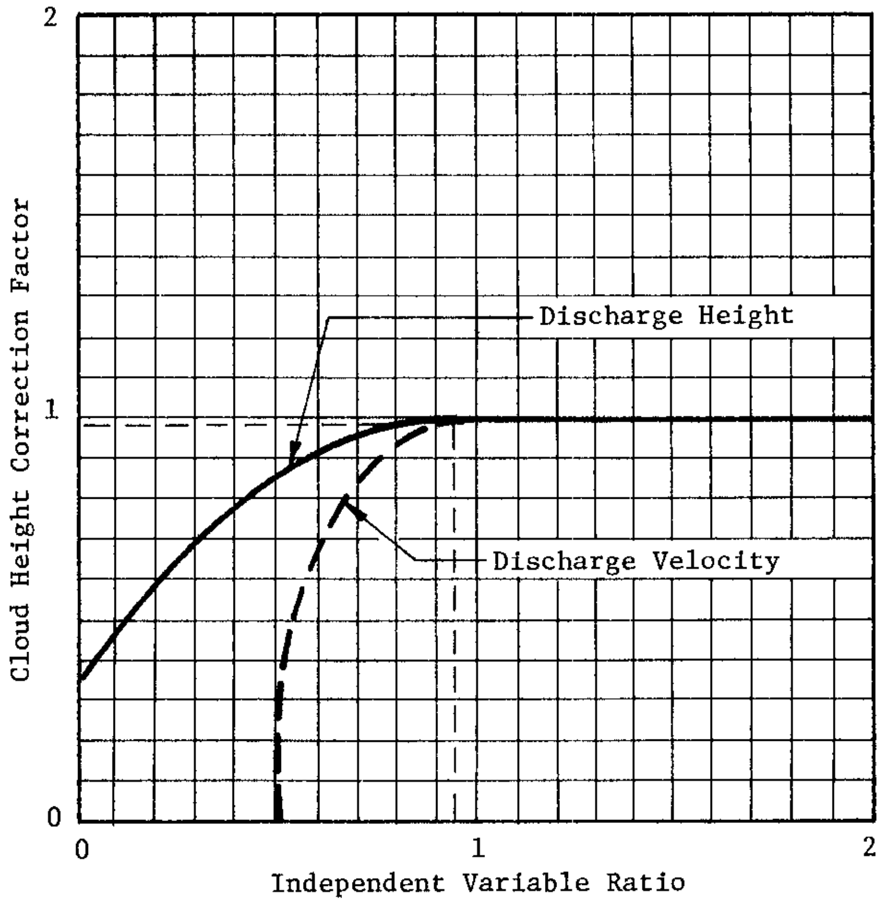
Sediment = clayey silt
Concentration = 17 percent solids by weight

Figure 59. Head wave velocity corrections for off-reference conditions using the diffuser



Sediment = clayey silt
Concentration - 17 percent solids by weight

Figure 60. Mud flow height corrections for off-reference conditions using the diffuser



Sediment = sandy silt
Concentration = 17 percent solids by weight

Figure 61. Cloud height corrections for off-reference conditions using the diffuser

operated on the bottom to maximize the mud flow density and minimize the water column turbidity at the discharge point. Of course, the processor must be raised gradually as the sediment mound grows. For purposes of the calculated prediction the height-off-the-bottom is zero.

206. The case properties for the test model (based on test 40), full-scale reference model, and full-scale corrected model are summarized below.

Case	Model (test 40)	Full-Scale Prediction Reference	Full-Scale Prediction Corrected
Pipe Diameter, in.	1.049	24	24
Scale Factor	1.0	22.9	22.9
Discharge Velocity, fps	4.0	19.1	18.0
Discharge Height, ft (in.)	(2)	3.8	0
Head Wave Velocity, fps	.089	.426*	0.28 (Figure 59)
Mud Flow Height, ft (in.)	(1.75)	3.34*	1.84 (Figure 60)
Cloud Height, ft (in.)	(3)	5.72*	1.89 (Figure 61)

*Figure 58.

The full-scale reference case is obtained by scaling the test model dimensions (discharge height) by the scale factor 22.9 (i.e., 24 ÷ 1.049 = 22.9) and the discharge velocity by the square root of the scale factor (i.e., 4.0 x 4.78 = 19.1). The scaled reference data for the dependent variables are shown in Figure 58. The full-scale corrected case differs from the reference case in the values for discharge velocity (18 fps versus 19.1) and discharge height above the bottom (0 ft versus 3.8 ft).

The correction factors for these differences are developed below based on the correction curves shown in Figures 59, 60, and 61, where

$$\underline{\text{Discharge Velocity Ratio}} = \frac{18}{19.1} = 0.94$$

and

$$\underline{\text{Discharge Height Ratio}} = \frac{0}{3.8} = 0$$

are the independent variable ratios.

<u>Headwave Velocity Correction</u>

for discharge height = 0.67 (Figure 59)

for discharge velocity = 1.00 (Figure 59)

total correction factor = (0.67)(1.00) = 0.67

corrected headwave velocity = (0.426)(0.67) = 0.28 fps

<u>Mud Flow Height Correction</u>

for discharge height = .57 (Figure 60)

for discharge velocity = 0.96 (Figure 60)

total correction factor = (0.57)(0.96) = 0.55

corrected mud flow height = (3.34)(0.55) = 1.84 ft

<u>Cloud Height Correction</u>

for discharge height = 0.33 (Figure 61)

for discharge velocity = 0.99 (Figure 61)

total correction factor = (.33)(0.99) = 0.33

corrected cloud height = (5.72)(0.33) = 1.89 ft

207. The results of the foregoing prediction calculations can be used to compare the performance of the 20 deg submerged pipe and the diffuser processor on the same dredging operation. Each discharge system was evaluated at a second height above bottom to show how its performance might change with vertical adjustment. The 20 deg submerged pipe was evaluated at 8 ft and 14 ft off the bottom and the diffuser was evaluated on the bottom and 3 ft above bottom. The additional points were determined by the procedures followed in the above illustrative examples. The predicted performance data are presented below in Table 8.

Table 8

Full Scale Performance Predictions

	20 deg Submerged Pipe		Diffuser Processor	
Height Above Bottom, ft	8	14	On bottom	3
Head Wave Velocity, fps	1.02	1.12	0.28	0.38
Mud Flow Height, ft	4.35	4.62	1.84	2.94
Cloud Height, ft	7.18	10.5	1.89	5.49

Note: Pipeline ID = 24 in.
Pipeline flow velocity = 18 fps

208. Several trends are evident from the information in Table 8. When resting on the bottom the diffuser produces a slow-moving mud flow less than 2 ft thick with virtually no turbidity cloud and hence represents the ultimate in mud flow control. As the diffuser is raised 3 ft off the bottom the fluid mud layer thickens by about one ft, the turbidity cloud becomes 2.5 ft thick, and the top of the cloud is now

almost three times higher than it was with the diffuser on the bottom. The diffuser control over the mud flow can therefore be varied widely by relatively small adjustments in the height of the diffuser above the mound surface. To reduce the height of the turbid cloud the diffuser should be operated as close to the mound surface as practicable without burying it. Lowering the end of the 20 deg submerged pipe from 14 to 8 ft above the bottom does not alter the fluid mud layer appreciably but it does reduce the cloud height by about 30 percent. The 24 in. pipe discharging at 18 fps (25,400 gpm) cannot be lowered closer than 8 ft above bottom without incurring severe bottom scour.

209. The operating conditions in Table 8 represent the best and the least performance for each discharge system which allows the best and the least favorable comparison of the diffuser with respect to the 20 deg submerged pipe. The diffuser looks best operating on the bottom. Compared with the 20 deg submerged pipe 14 ft above bottom, the diffuser reduces the thickness of the fluid mud layer by a factor of 2.5 (4.62 ÷ 1.84) and the cloud height by a factor of 5.5 (10.5 ÷ 1.89). The worst view of the diffuser occurs with it operating 3 ft above bottom as compared to the 20 deg pipe mounted 8 ft above bottom. In this case the diffuser reduces the mud flow thickness by a factor of 1.5 (4.35 ÷ 2.94) and the cloud height by a factor of nearly 2 (10.5 ÷ 5.49 = 1.9). Although the effectiveness of the diffuser in reducing cloud height can vary widely from 5.5:1 to 1.9:1, the lower value still represents significant superiority of the diffuser.

CHAPTER VII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Submerged discharge is an effective technique for reducing the turbidity associated with the disposal of fine-grained dredged material by open-water discharge. Flume tests have shown that a submerged open pipe discharge generates less turbidity in the water column than an open pipe discharge above the surface. Further lessening of turbidity has been demonstrated using a diffuser, rather than an open pipe, for submerged discharge.

An open pipe, submerged and oriented vertically downward, appears to yield significant reductions in turbidity generation compared to above-surface discharge. Three tests in this mode produced cloud heights of less than four inches. Two tests with above-surface discharge produced cloud heights of nine and eleven inches, respectively.

All processor models tested were similar to, or better than, the open-pipe submerged discharge configuration in reducing turbidity compared to the above-surface discharge. Two models, the diffuser and the plenum, were about equal in performance, as measured by mud flow height and cloud height. These models were distinctly superior to the shroud and the weir, neither of which demonstrated noticeable improvement over the open-pipe submerged discharge.

The diffuser reduced head wave velocity by more than 50% from the baseline conditions over a wide range of test conditions.

Froude number scaling can be used to predict full-scale behavior of dredged material discharges based on tank tests. An example computation showed that a diffuser processor can provide a cloud height of 2 ft off the bottom, while a 20 deg submerged pipe would produce an 11 ft cloud height.

Engineering analysis has shown that a complete full-scale submerged discharge system can be fabricated from conventional materials with conventional manufacturing techniques. A prototype total system, including the processor and a specially designed or modified barge, using an 18-in. pipeline, could be produced for approximately $212,000 (1977 prices).

For a full-scale system to be effective in reducing turbidity, the processor must be close to the bottom. On the other hand, it must not be allowed to be buried by the rising mound of discharged material. A simple model of the mounding of dredged material has shown that a processor would need to be moved approximately four to five times during a month of disposal operations. This level of maintenance does not appear unduly burdensome for a typical hydraulic pipeline dredging project with the normal complement of workboats and labor.

Recommendations

The concepts developed and tested in this project should be field tested at full scale. The goals of the field test should be:

a. Verify the scale-up computation approach used in this report;

b. Verify the approach to computing required processor movements.

The field test design should include:

a. Comparison of open-pipe discharge above the surface, open-pipe submerged discharge, and at least one processor model;

b. Plans for measuring turbidity, mud flow velocity, mud flow thickness, ultimate propagation distance of mud flow, and mounding behavior at the discharge point.

LITERATURE CITED

1. Federal Register, Vol. 40, No. 173, Friday, Sept. 5, 1975. Environmental Protection Agency Rules and Regulations governing the discharge of dredged or fill material into navigable waters.

2. May, E.B., "Environmental Effects of Hydraulic Dredging in Estuaries," Alabama Marine Resources Bulletin, No. 9, Dauphin Island, Alabama, April, 1973.

3. U.S. Army Corps of Engineers, Mobile District Office, "Surveillance Program of Sedimentation Effects of Hydraulic Dredging," Mobile, Alabama, January, 1968.

4. Migniot, C., "A Study of the Physical Properties of Various Very Fine Sediments and their Behavior under Hydrodynamic Action," presented to the "Comite Technique de la Société Hydrotechnique de France," March 22, 1968.

5. Middleton, G.V., "Small-Scale Models of Turbidity Currents and the Criterion for Auto-Suspension," Journal of Sedimentary Petrology, Vol. 36, No. 1, March, 1966.

6. Nichols, M.M., et al., "A Field Study of Fluid Mud Dredged Material: Its Physical Nature and Dispersal," Technical Report D-78-40, 1978, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi.

APPENDIX A: NOTES OF THE SURVEY OF CORPS OF ENGINEERS DISTRICT OFFICES AND PRIVATE DREDGING CONTRACTORS

1. As an aid in the development of concepts for submerged discharge pipeline designs, a survey was conducted by telephone to determine what experience and expertise have been gained by the dredging industry in the submerged discharge technique. District offices of the Corps of Engineers that were known to be involved in dredging projects were contacted and questioned as were several of the private dredging contractors that have been involved in open-water discharge operations. Those that indicated experience with submerged discharge were asked the following questions:

- a. Why did you use a submerged discharge?
- b What were the details of the configuration?
- c. What results did you obtain?
- d. What are your recommendations for the use of the submerged discharge technique?

The following is a summary of the notes for each telephone interview.

Agency/Company Contacted: U.S. Army Engineer District, Portland
Individual Interviewed: Mr. Gregory Hartman
Date: July 1976

2. Submerged discharge has often been used in the upper Columbia River because of the need for accurate placement of material on the river bottom. The material dredged from the Columbia River consists mainly of clean sand that sinks rapidly to the river bottom after being released into the water column. The high sinking rate creates a mounding

problem that is alleviated only by continuously moving the discharge pipe. Because the sand in these areas is clean, little turbidity is visible at the water surface regardless of discharge technique.

3. Mr. Lou Smith of the Portland District has studied submerged discharge where turbidity (as a function of water depth) during discharge was one of the measured variables. The report on this work had not been prepared at the time of this telephone call.

Agency/Company Contacted: U.S. Army Engineer District, St. Paul

Individual Interviewed: Mr. Raymond Sanford

Date: July 1976

4. The St. Paul District tested submerged discharge in 1975 as a means of reducing turbidity during discharge operations. Even though the material being discharged was sandy, it produced significant turbidity when discharged above the water's surface. The District discharged material into a pond using a submerged 80-ft bleeder (slotted) pipe. An attempt was made to avoid mounding by discharging over a wide area. Results of the experiment showed very little reduction in turbidity using submerged discharge, and further use of the technique was discontinued.

Agency/Company Contacted: U.S. Army Engineer District, Norfolk

Individual Interviewed: Mr. Thomas Lawless

Date: July 1976

5. The Norfolk District uses the submerged discharge technique as a means of precise placement of material. Bleeder pipes, deflector plates on the end of the discharge pipe, and submerged discharge have

all been used to achieve both turbidity reduction and placement accuracy.

Agency/Company Contacted: U.S. Army Engineer District, Jacksonville

Individual Interviewed: Mr. Keith Hamilton

Date: September 1976

6. The Jacksonville District has performed submerged discharge in 6-8 ft of water with the discharge pipe pointed vertically downward approximately 1 ft below the water surface. Submerged discharge was first tested approximately 4 years ago as a method for the accurate placement of dredged material. Turbidity reduction was not a consideration when the decision to use submerged discharge was made. Since the Jacksonville District deals mainly with sand, their experiences with the procedure have been similar to those of the Portland District, i.e., visual observations indicate that turbidity was not reduced significantly during discharge while significant mounding did occur.

Agency/Company Contacted: U.S. Army Engineer District, Mobile

Individual Interviewed: Mr. Patrick Langan

Date: September 1976

7. In 1974 the Mobile District tried submerged discharge by placing discharge pipe 2-3 ft below the water surface. In Mr. Langan's opinion, the resulting turbidity was less than that generated with above-water discharge, but the mud flow was increased. Only visual observations were made in this attempt, so firm conclusions could not be drawn.

Agency/Company Contacted: U.S. Army Engineer District, Sacramento

Individual Interviewed: Mr. James McBride

Date: September 1976

8. The Sacramento District has used submerged discharge, but can no longer use open-water discharge of any kind due to environmental restrictions. Mounding was not a problem since they required their contractors to maintain a mean water depth of 4 ft. No field observations had been made concerning reduction of turbidity using the technique.

Agency/Company Contacted: U.S. Army Engineer District, Philadelphia

Individual Interviewed: Mr. Stanley Snarski

Date: July 1976

9. Discharge of dredged material into the Delaware Bay and tributary waters is prohibited to minimize the impact of dredging on the aquatic environment. As a result, the Philadelphia District has had no recent experience with the submerged discharge technique. Mr. Snarski thought that a deflector plate would be necessary for the submerged discharge technique to be successful in reducing turbidity. He referred questions to Mr. Vince Calvarese, Chief of Engineering Branch. Mr. Calvarese stated that he had no experience with submerged discharge and, consequently, could be of no help. Dr. William Barnard of the U.S. Army Engineer Waterways Experiment Station has advised that in 1967, the Philadelphia District used submerged discharge with the pipe pointing down and with a deflector plate.

Agency/Company Contacted: U.S. Army Engineer District, Buffalo

Individual Interviewed: Mr. Gerry Greener

Date: September 1976

10. The Buffalo District has never used submerged discharge since all dredged material disposal is performed with dump barges rather than pipelines.

Agency/Company Contacted: U.S. Army Engineer District, Chicago

Individual Interviewed: Mr. Bernard Bochantin

Date: July 1976

11. The Chicago District has no experience with the submerged discharge technique of dredged material disposal.

Agency/Company Contacted: U.S. Army Engineer District, Detroit

Individual Interviewed: Mr. T. Odle

Date: July 1976

12. The Detroit District has no experience with submerged discharge.

Agency/Company Contacted: U.S. Army Engineer Division, New England

Individual Interviewed: Mr. William McCarthy

Date: July 1976

13. The New England Division does not use open-water discharge during hydraulic pipeline dredging operations.

Agency/Company Contacted: U.S. Army Engineer District, Galveston

Individual Interviewed: Mr. Dolan Dunn

Date: September 1976

14. The Galveston District assigns dredging operators areas in which to discharge dredged material but does not specify any particular discharge technique. A contractor in the Corpus Christi area is presently using the submerged discharge technique, but no effort is being made to monitor turbidity during the operation.

Agency/Company Contacted: U.S. Army Engineer District, Baltimore

Individual Interviewed: Dr. C. Kearns

Date: July 1976

15. Dr. Kearns knew of an instance in which one of the Baltimore District dredging contractors used the submerged discharge technique. The contractor used a deflector plate on the end of the discharge pipe to prevent mounding since he was required to maintain a minimum water depth of 3.5 ft. Because no effort was made to monitor the project, judgments concerning turbidity reduction could not be made.

Agency/Company Contacted: U.S. Army Engineer District, Charleston

Individual Interviewed: Mr. Lawrence Snyder

Date: September 1976

16. The Charleston District has no knowledge of or experience with submerged discharge.

Agency/Company Contacted: U.S. Army Engineer District, Savannah

Individual Interviewed: Mr. William Young

Date: September 1976

17. Mr. Young had no knowledge of the Savannah District using submerged discharge.

Agency/Company Contacted: U.S. Army Engineer District, San Francisco

Individual Interviewed: Mr. John Sustar

Date: September 1976

18. The San Franciso District has not had any experience with submerged discharge.

Agency/Company Contacted: Parkhill Goodloe, Inc. Jacksonville, Fla.

Individual Interviewed: Mr. Michael Mashela

Date: December 1976

19. Parkhill Goodloe did not have any direct experience with submerged discharge. Mr. Mashela did question whether the technique could be of any value in an area with a strong current. He stated that since sand does not cause a turbidity problem when discharged, submerged discharge is of potential value in reducing turbidity only when disposal of silt or clay is involved. According to Mr. Mashela, silt and clay will remain in suspension regardless of where they are discharged in the water column when an ambient current is present. If the pipe is placed close to the bottom, the discharge process itself can cause resuspension of bottom

material, thus compounding the problem. Mr. Mashela concluded that submerged discharge would be of maximum value in lakes where ambient currents are small.

Agency/Company Contacted: Williams-McWilliams
Metairie, La.

Individual Interviewed: Mr. J. Miller

Date: January 1977

20. Williams-McWilliams uses submerged discharge extensively as a method for accurate placement of discharged material. Discharge baffles are employed for backfilling trenches because they spread the discharged material over a wider bottom area.

21. Williams-McWilliams does not use submerged discharge to reduce turbidity and hence has not attempted to quantify the difference in turbidity between above- and below-water discharge techniques. Visual observations, however, indicate reduced surface turbidity after submerging the discharge pipe.

Agency/Company Contacted: Atkinson Dredging Co.
Chesapeake, VA

Individual Interviewed: Mr. Bill Hull

Date: January 1977

22. Atkinson Dredging has used submerged discharge extensively in their operations. They discharge sandy (shell) silty material vertically into the water column, and most of the material drops rapidly to the bottom with very little suspended material rising to the water's surface. Visual surface turbidity is greatly reduced by discharging directly into the water column. Fine-grained material was dredged in the James River, with

disposal by submerged discharge, in July 1976. Visual observations indicated that surface turbidity was low.

Agency/Company Contacted:	Radcliff Materials, Inc. Mobile, Ala.
Individual Interviewed:	Mr. Robert Palmore
Date:	January 1977

23. Radcliff Materials has performed submerged discharge with the same results as other dredging companies that use the technique: visual turbidity was reduced by placing the discharge pipe into the water column. Radcliff was dredging a silty clay sediment.

Agency/Company Contacted:	The Hydrologic Engineering Center, Corps of Engineers, Davis, Cal.
Individual Interviewed:	Dr. Robert C. MacArthur
Date:	May 1977

24. In 1975 Dr. MacArthur conducted a laboratory study of several submerged discharge designs for the open-water discharge of fine-grained dredged material from a proposed dredging project in Los Angeles Harbor. The interest in submerged discharge was to minimize turbidity levels in the upper water column. As a result of his study, Dr. MacArthur recommended connecting the horizontal pipeline close to the upper end of a capped vertical cylindrical chamber (8 to 10 ft diameter corrugated pipe). The slurry flowed into the chamber from the pipeline, turned downward and decelerated as it gradually filled the larger flow area of the chamber, and exited radially through the annular opening between the lower edge of the cylinder and the harbor bottom. Bottom scour was to be minimized by using a deflector plate, and the entire assembly was

to be supported and adjustable by a system of vertical cables. Whether or not this design was built and operated is not known at this time.

APPENDIX B: CONCENTRATION PROFILES

1. For each of the runs conducted for both the baseline tests and the processor tests, water samples were taken to determine sediment concentration profiles vertically through the mud flow. These profiles served three purposes: to define the height of the mud flow, to determine the distribution of solids in the mud flow, and to establish an average density of the suspension comprising the mud flow.

2. Probes were arranged to take samples at each of three locations at seven different elevations above tank bottom: 1, 2, 3, 4, 6, 8, and 10 in. Concentrations were obtained by filtering the samples, and drying and weighing the solids. The profiles thus obtained are recorded in this appendix.

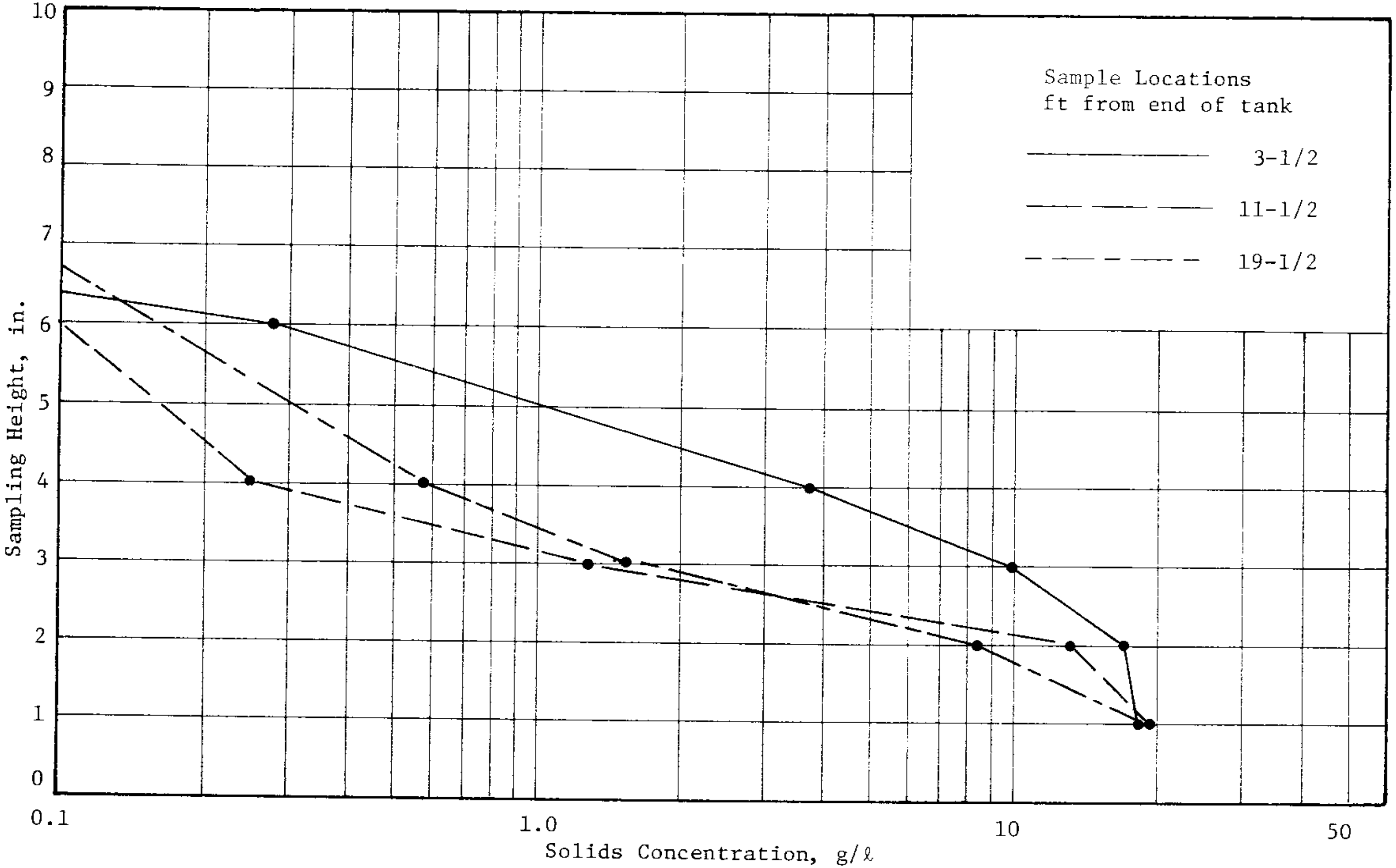


Figure B1. Concentration profiles, test 11

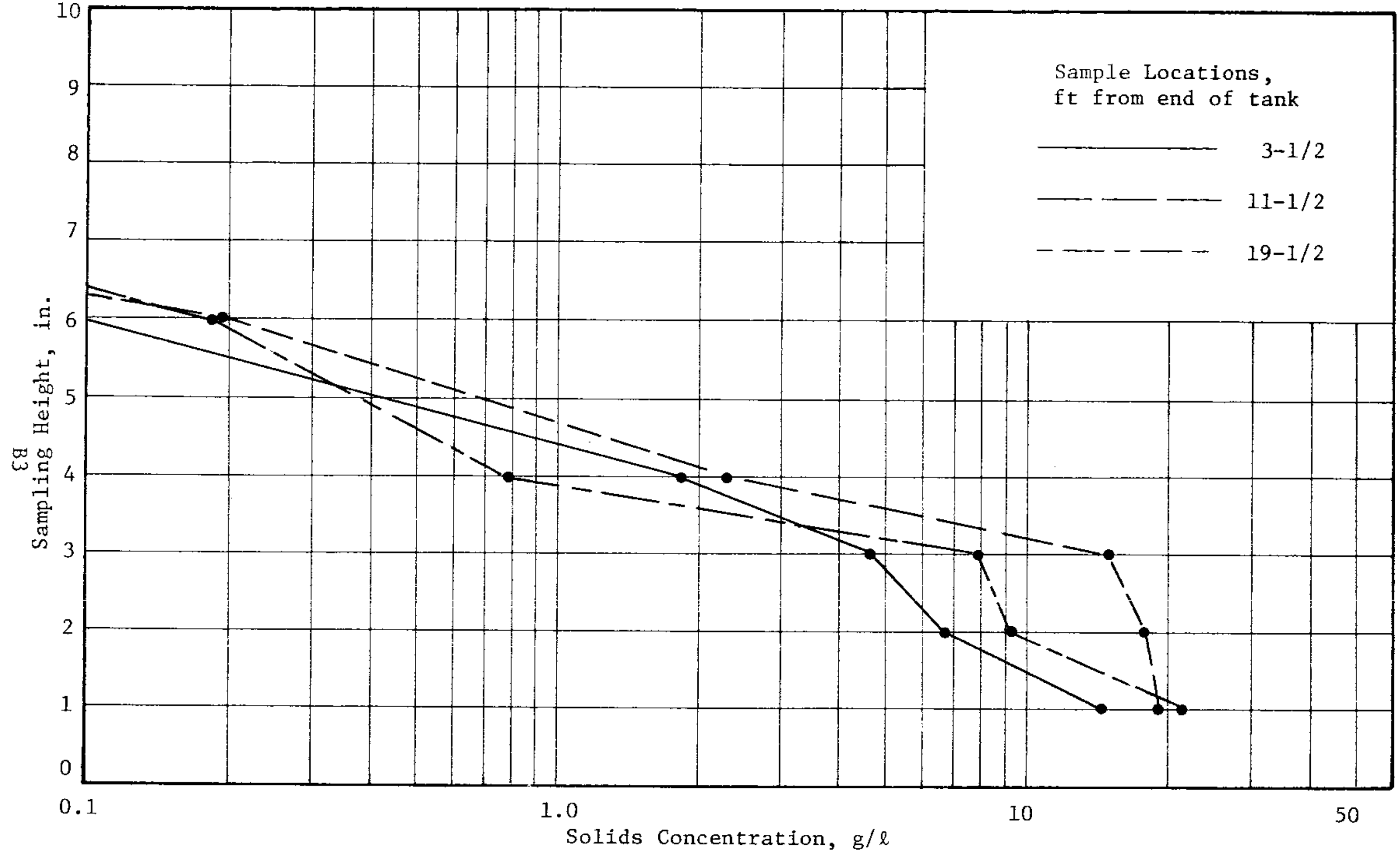


Figure B2. Concentration profiles, test 12

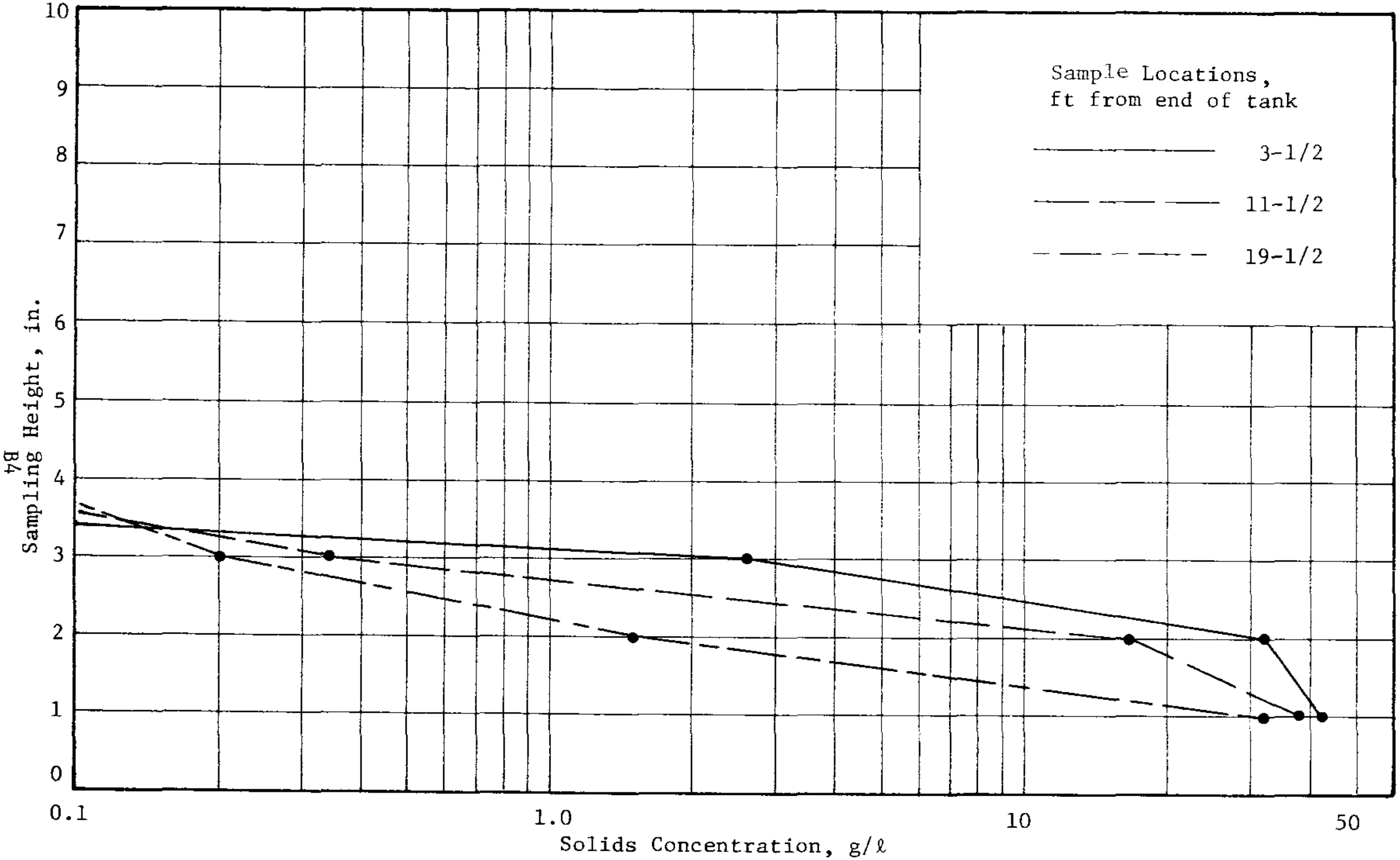


Figure B3. Concentration profiles, test 13

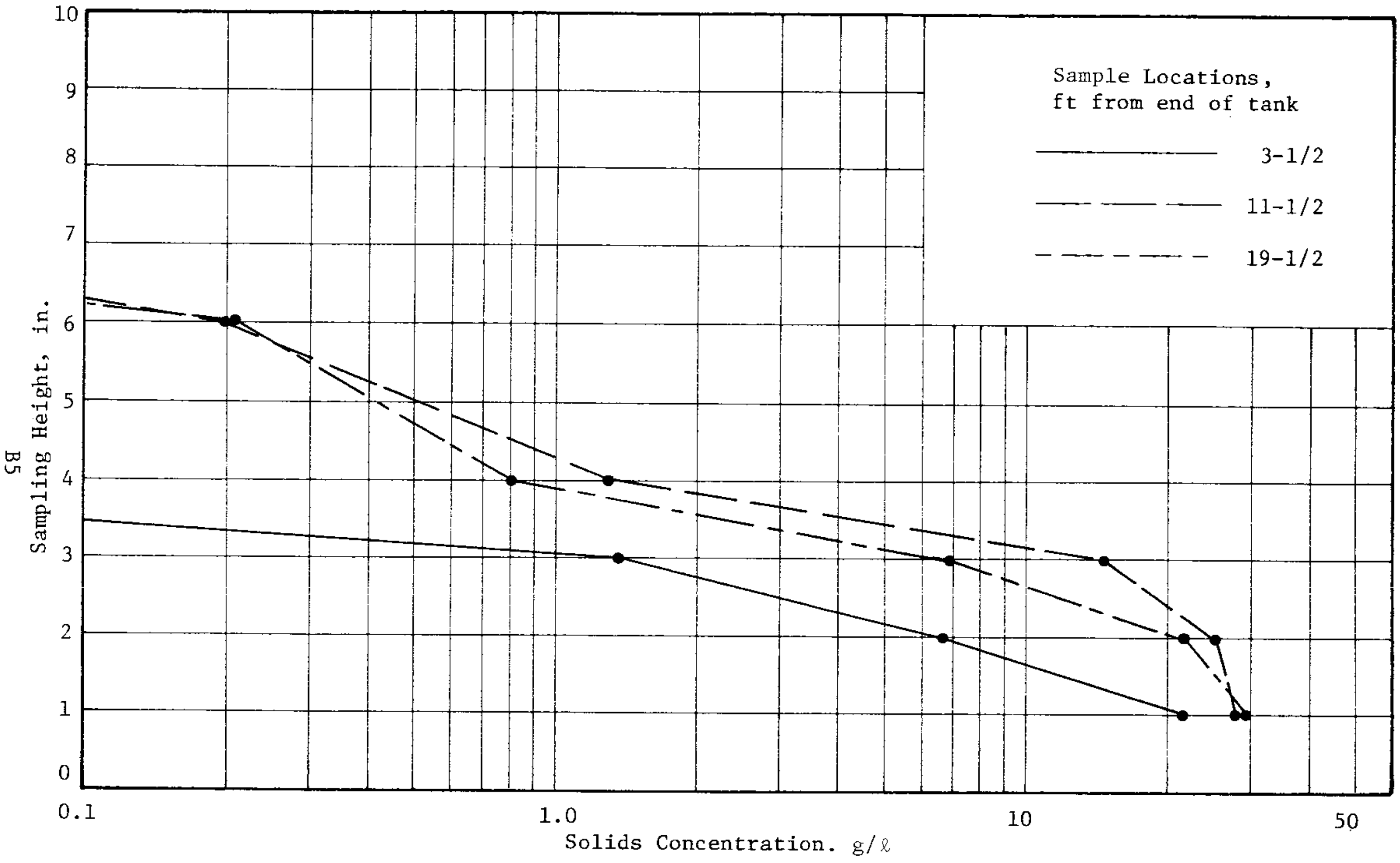


Figure B4. Concentration profiles, test 14

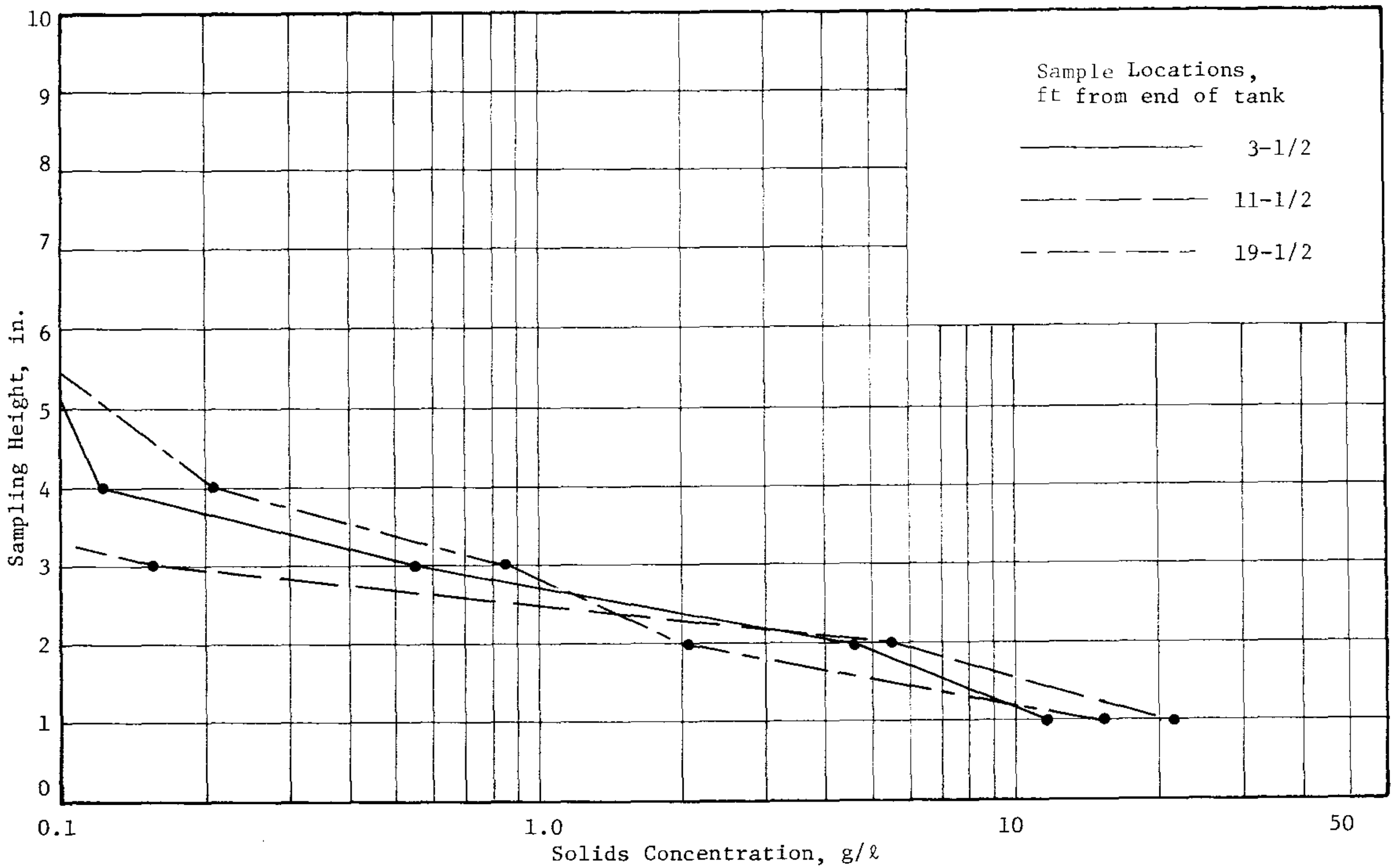


Figure B5. Concentration profiles, test 15

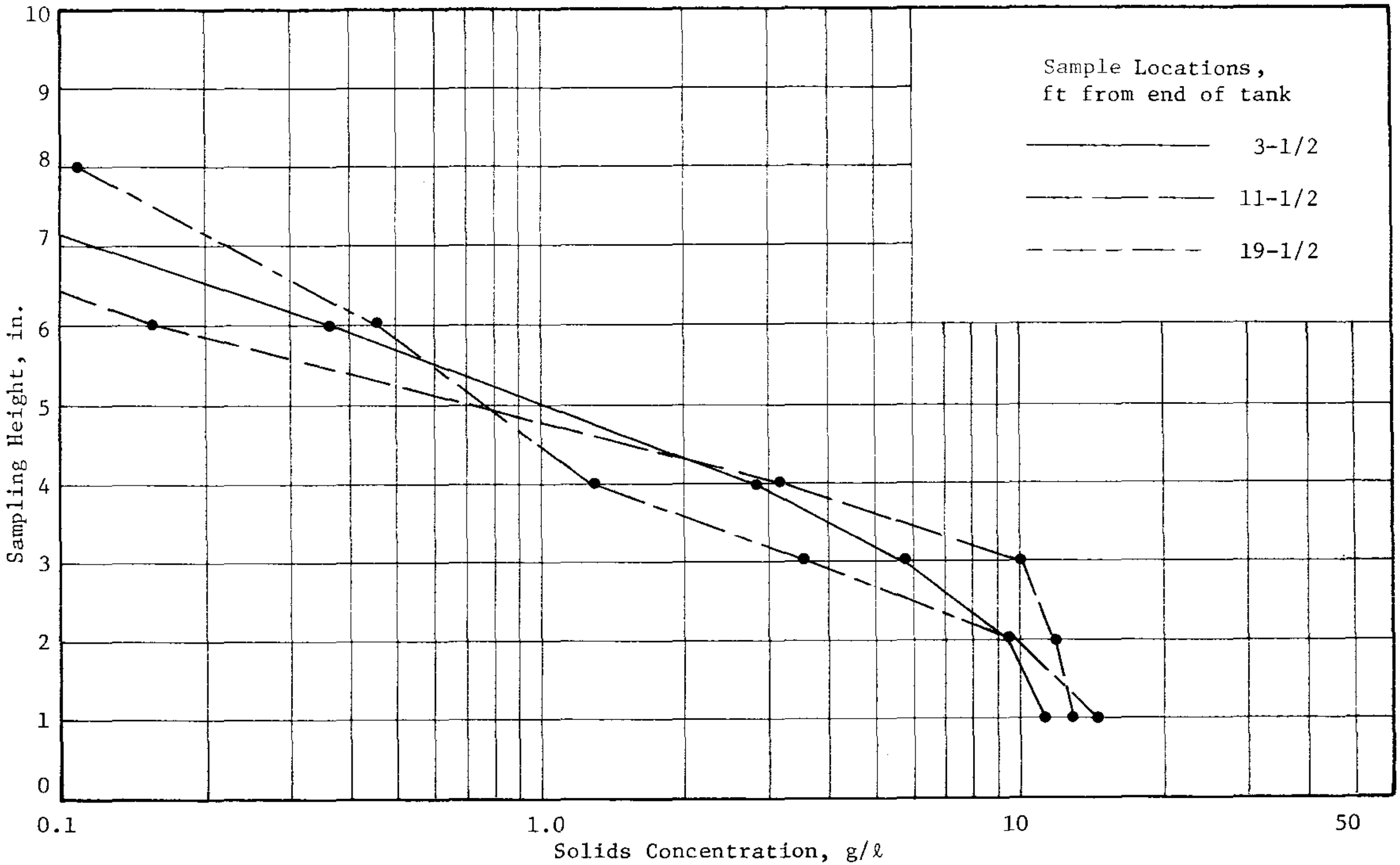


Figure B6. Concentration profiles, test 16

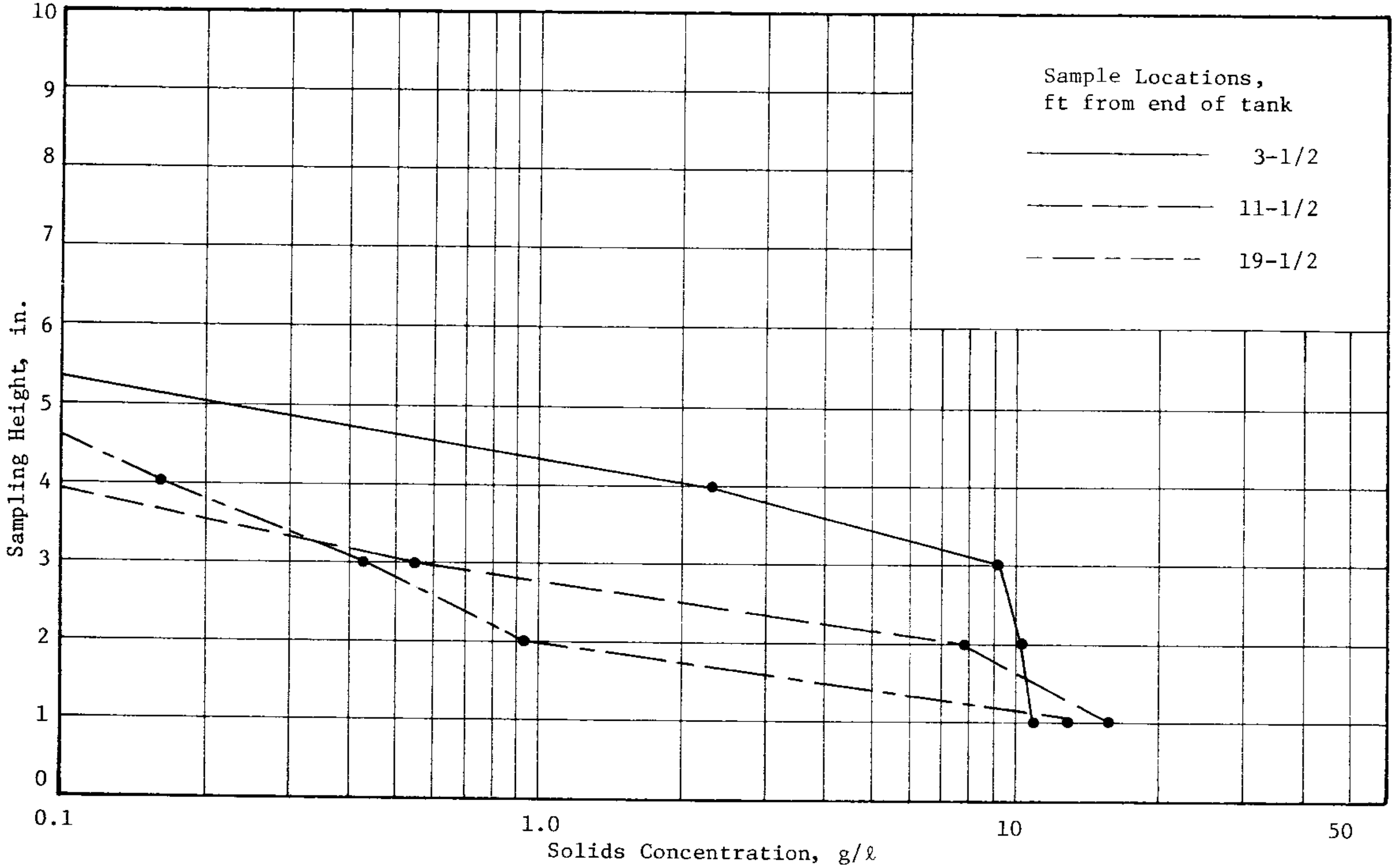


Figure B7. Concentration profiles, test 17

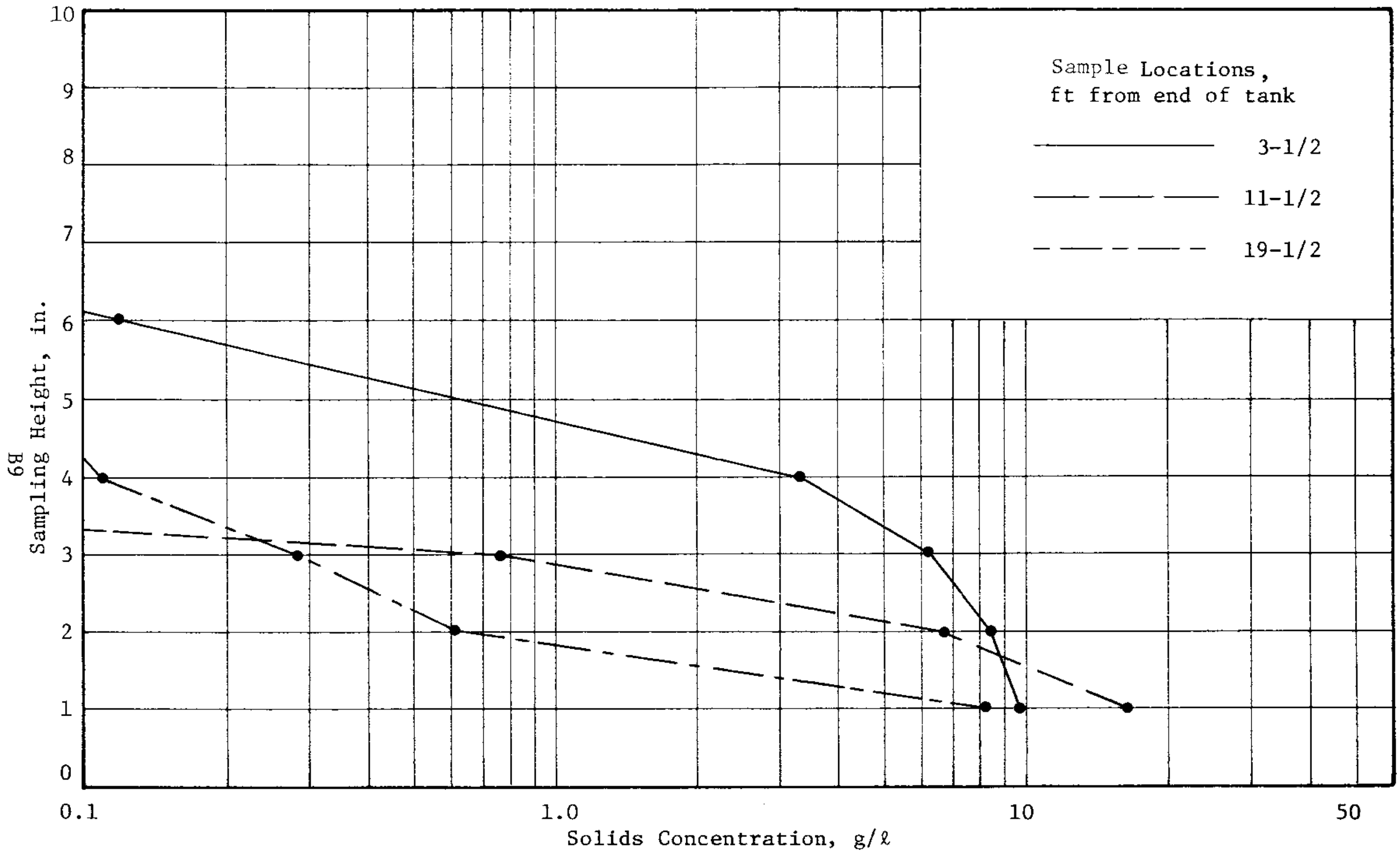


Figure B8. Concentration profiles, test 17[R]

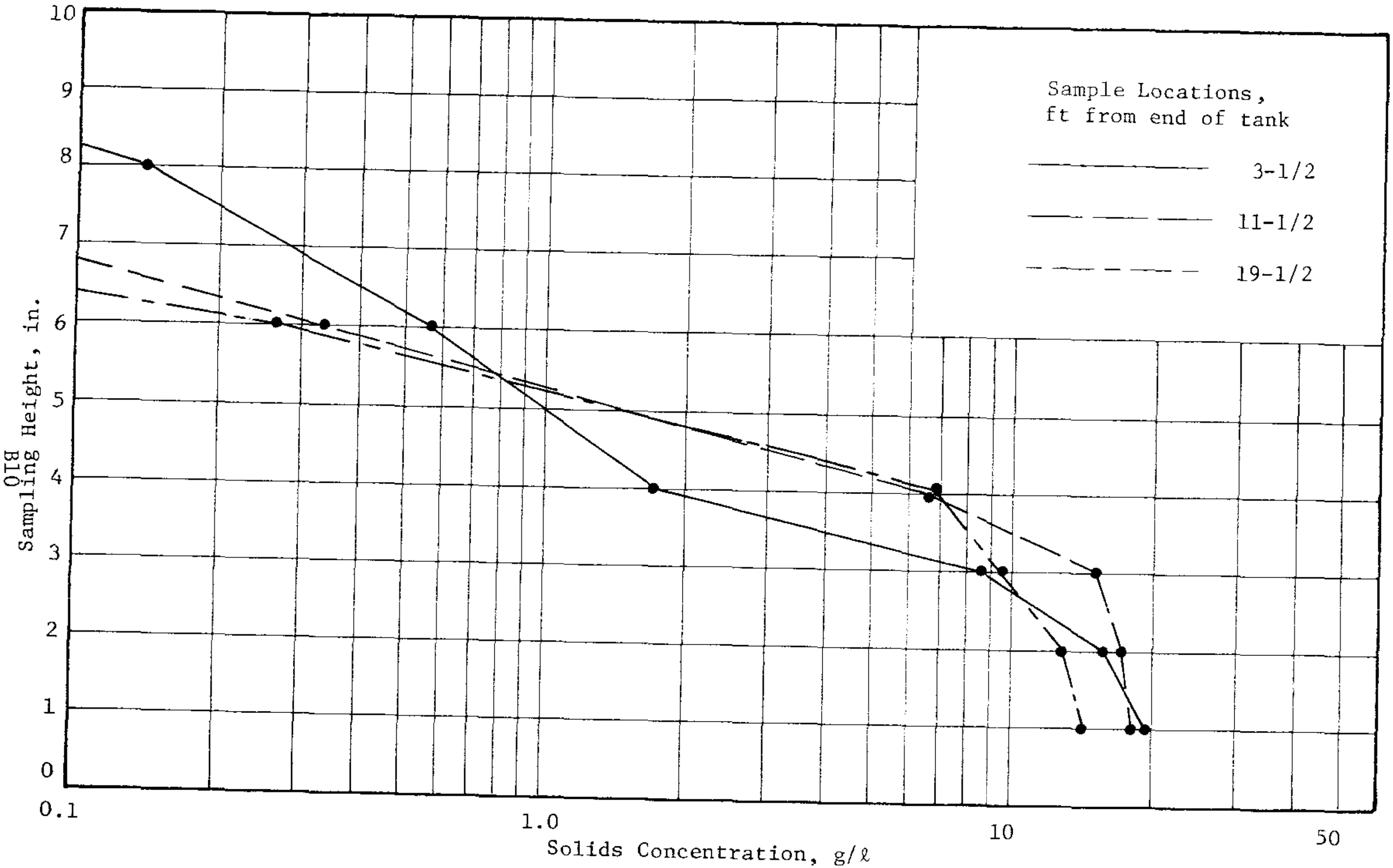


Figure B9. Concentration profiles, test 18

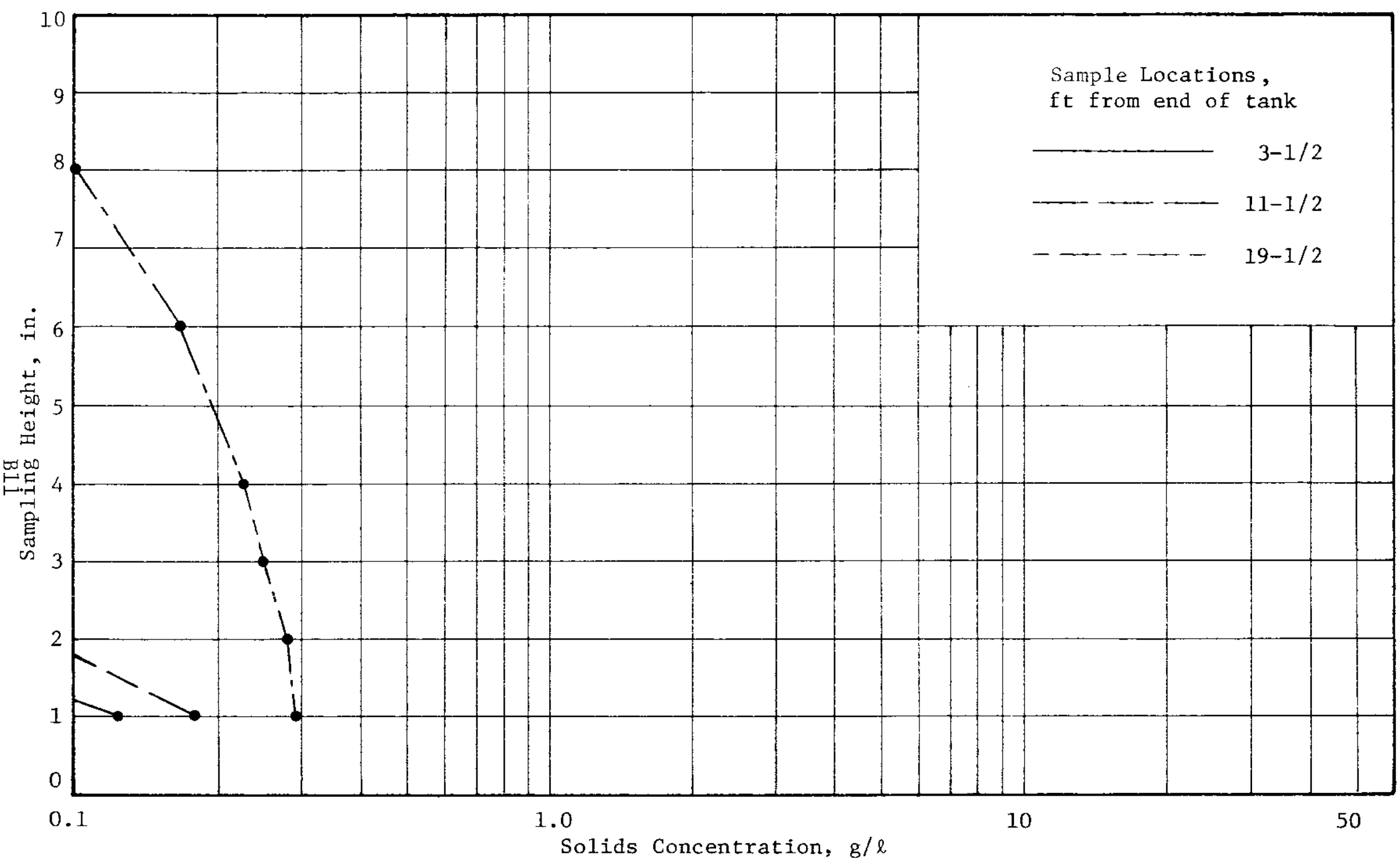


Figure B10. Concentration profiles, test 19

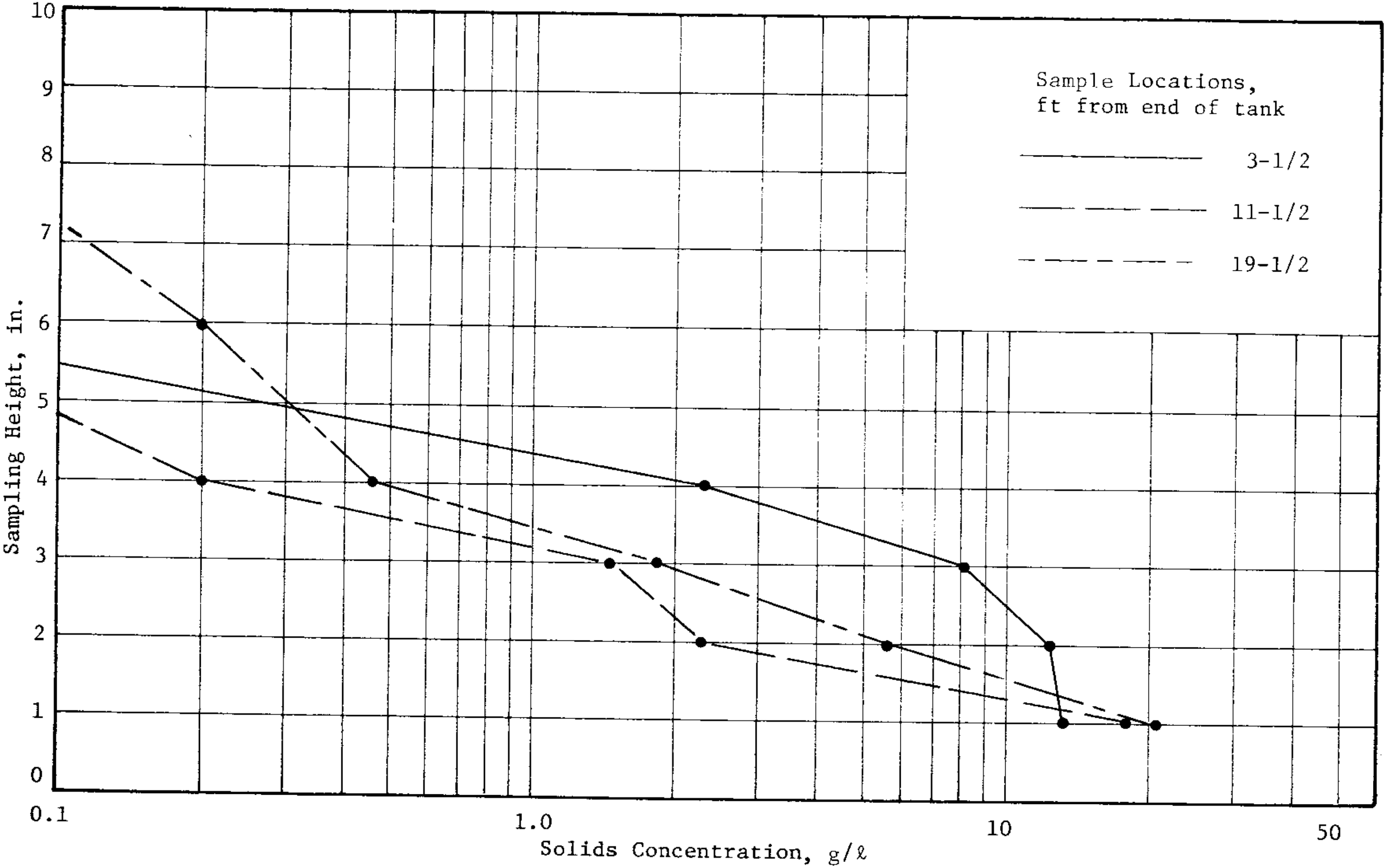


Figure B11. Concentration profiles, test 20

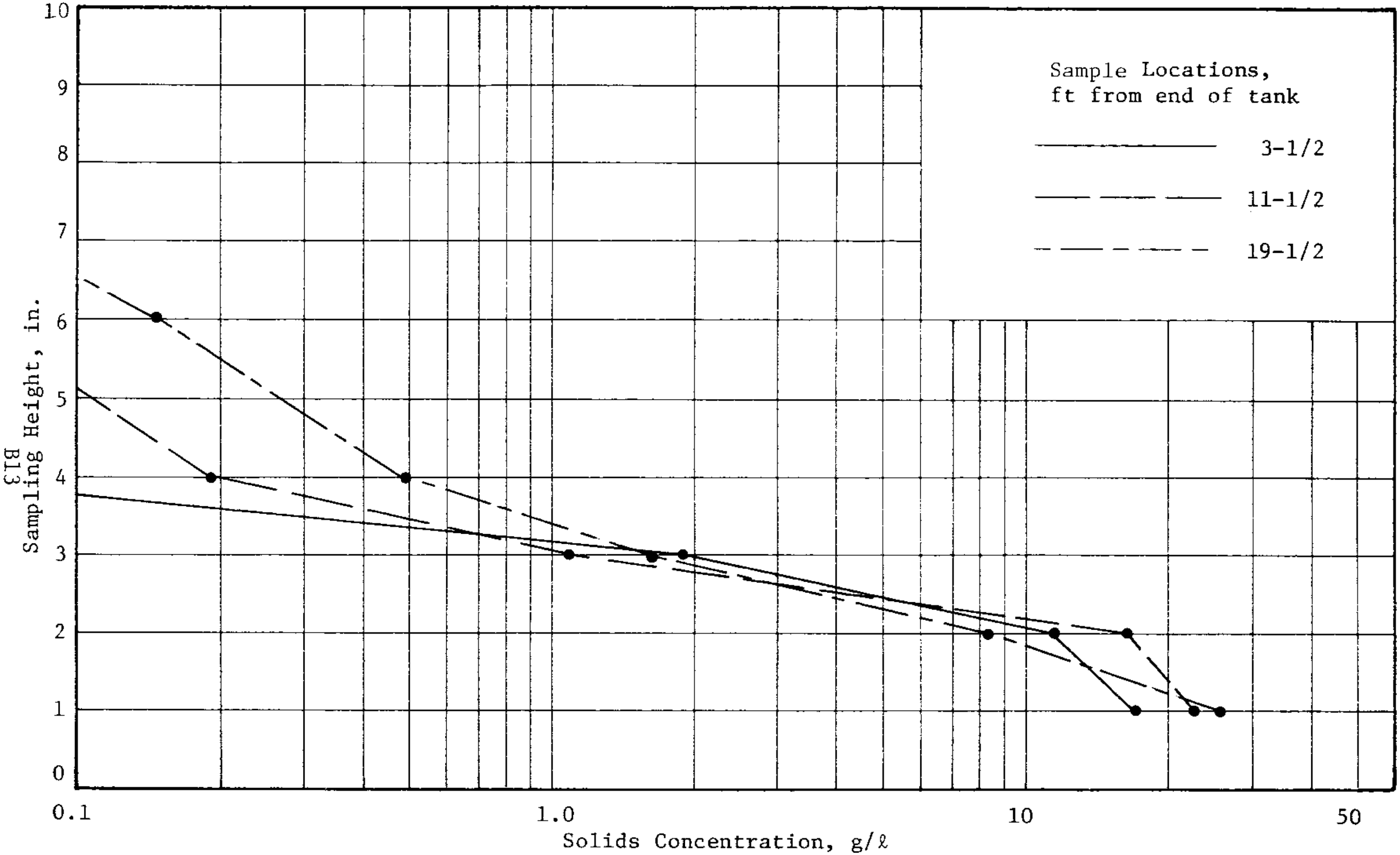


Figure B12. Concentration profiles, test 21

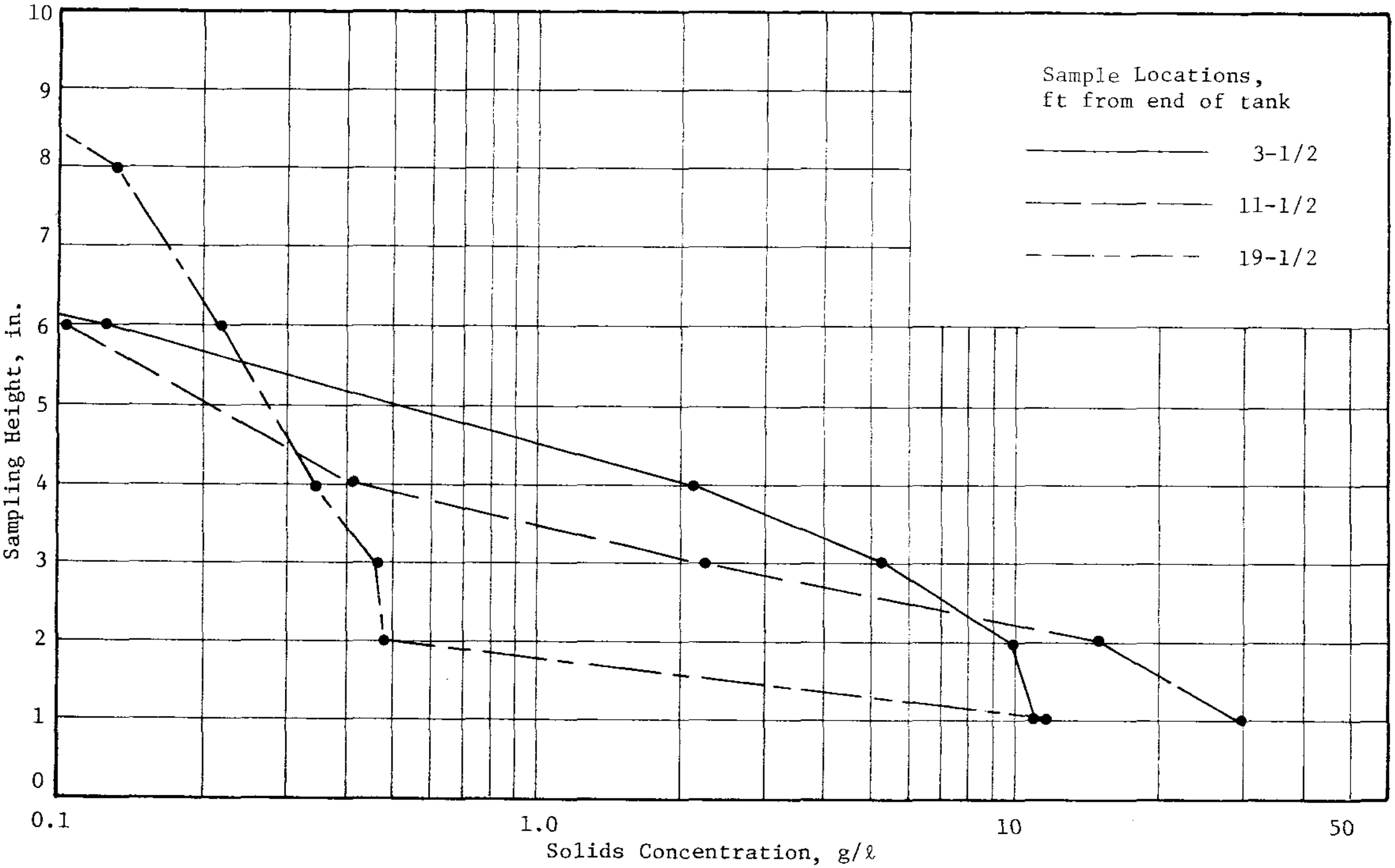


Figure B13. Concentration profiles, test 22

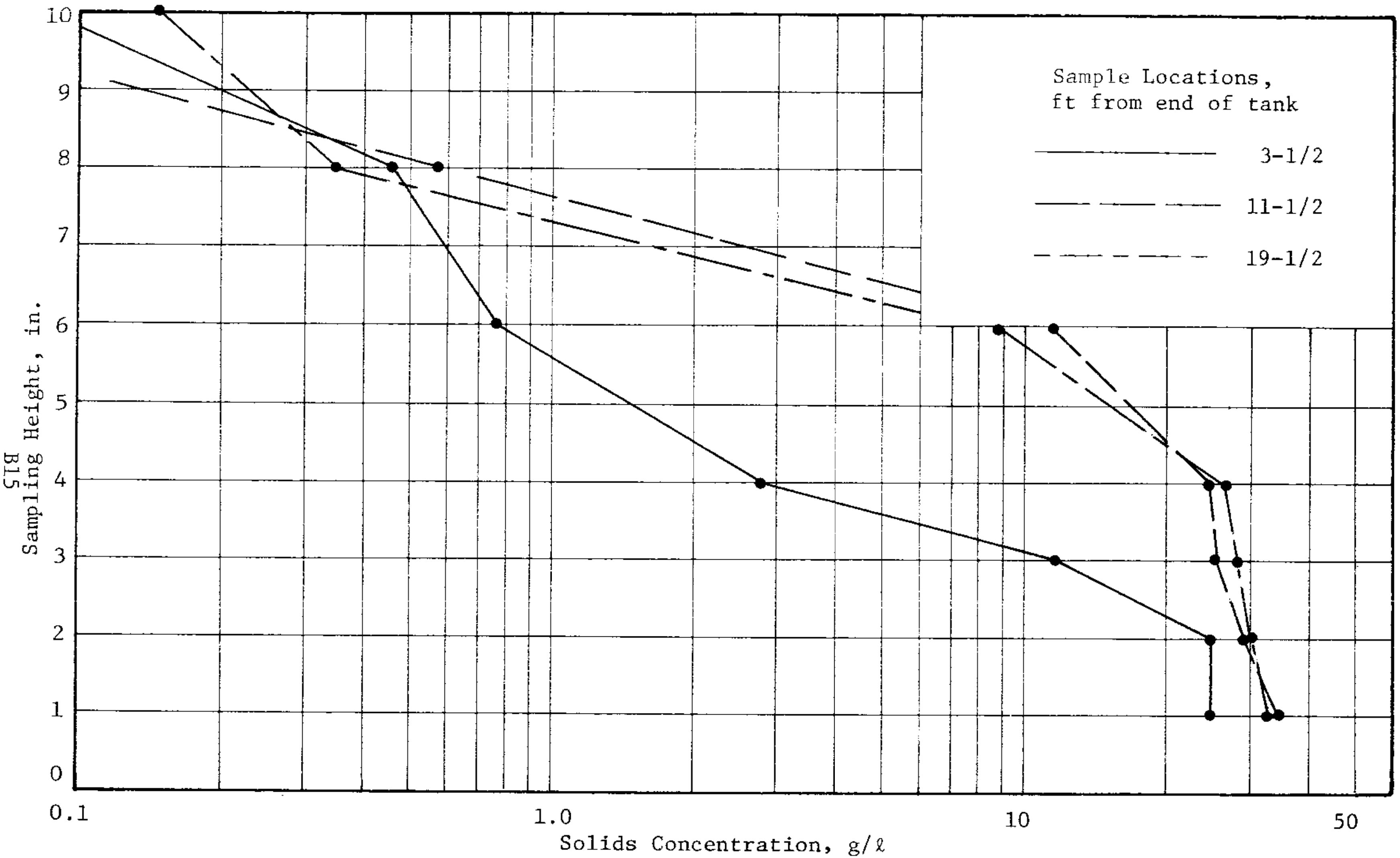


Figure B14. Concentration profiles, test 23

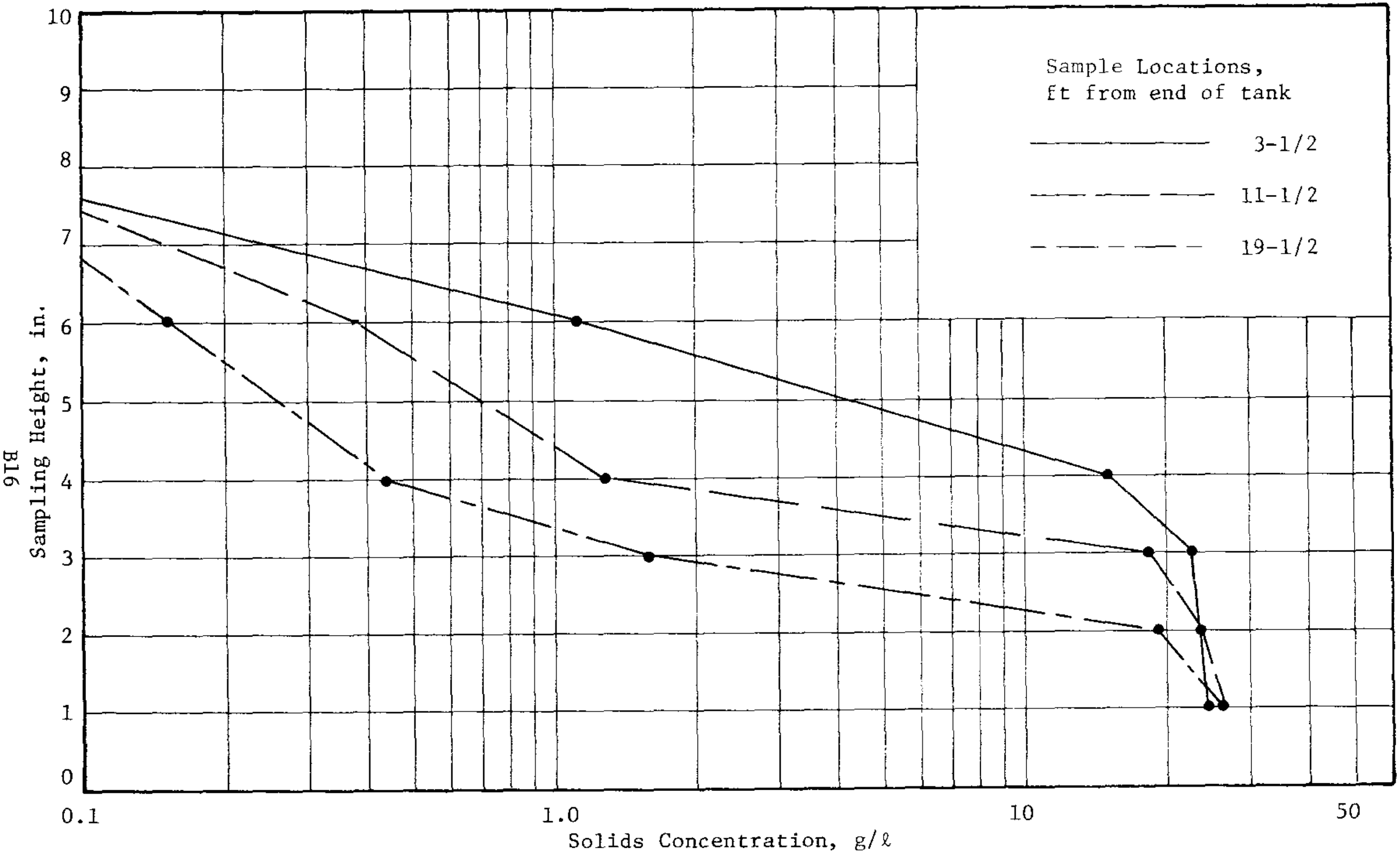


Figure B15. Concentration profiles, test 24

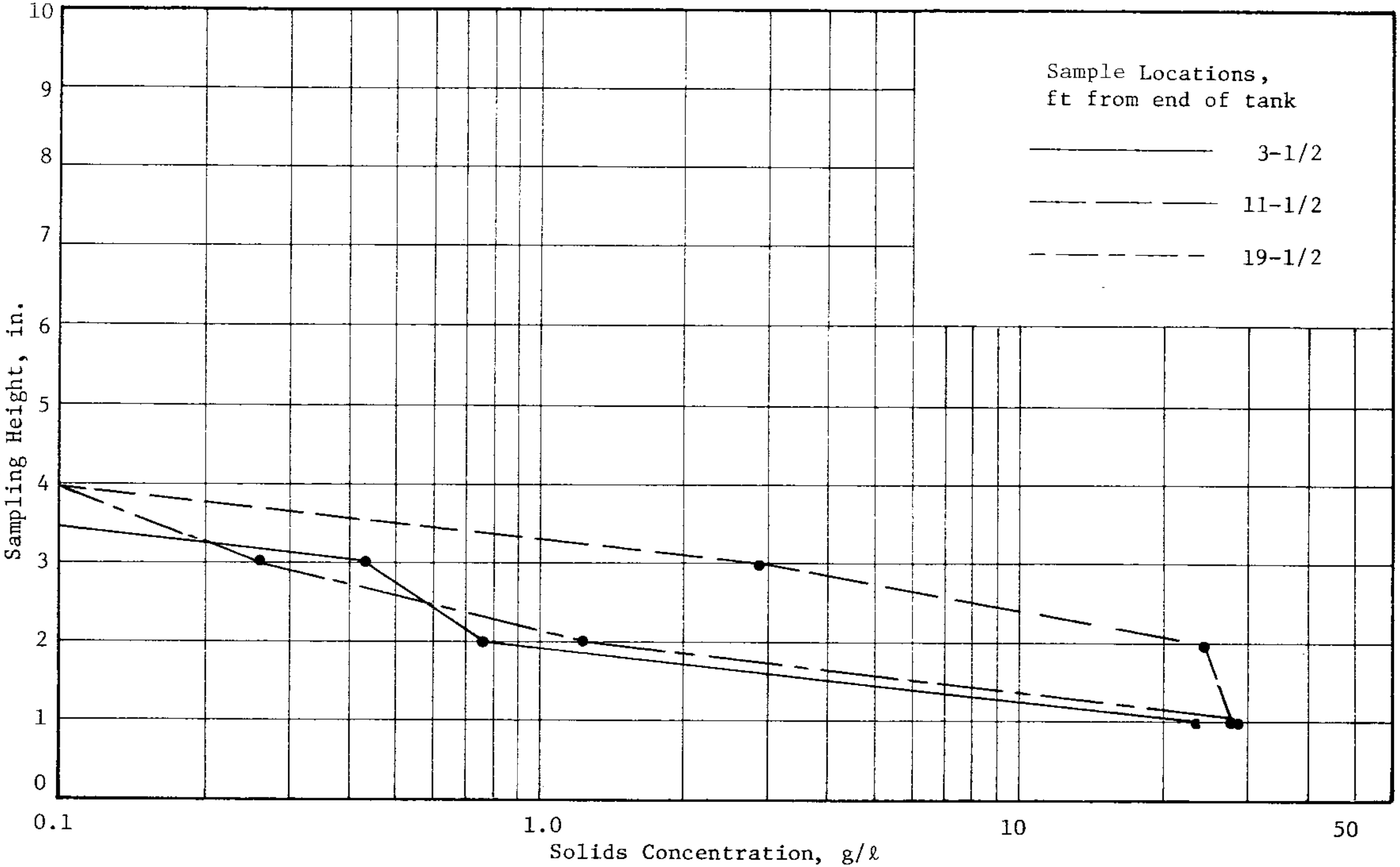


Figure B16. Concentration profiles, test 25

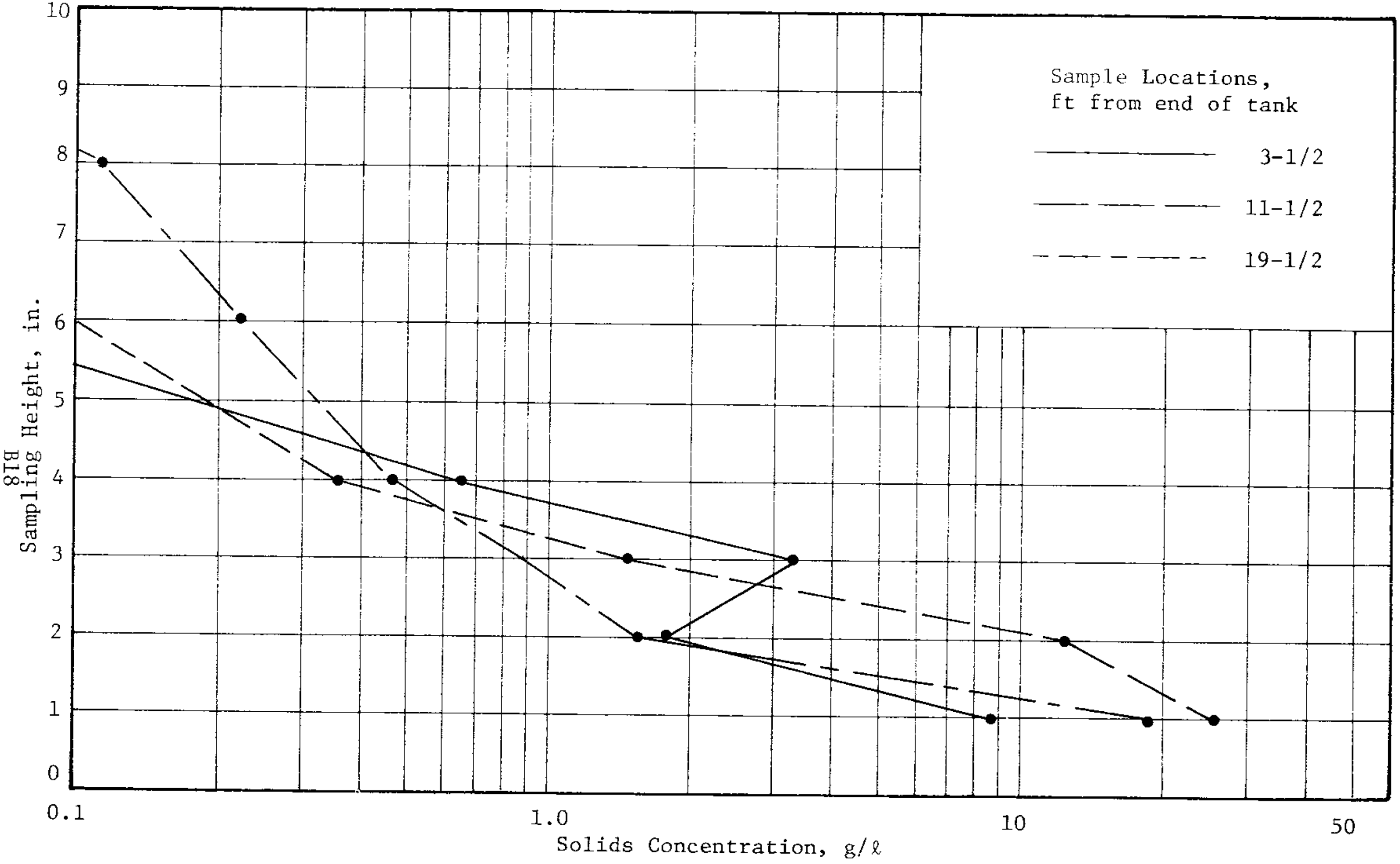


Figure B17. Concentration profiles, test 26

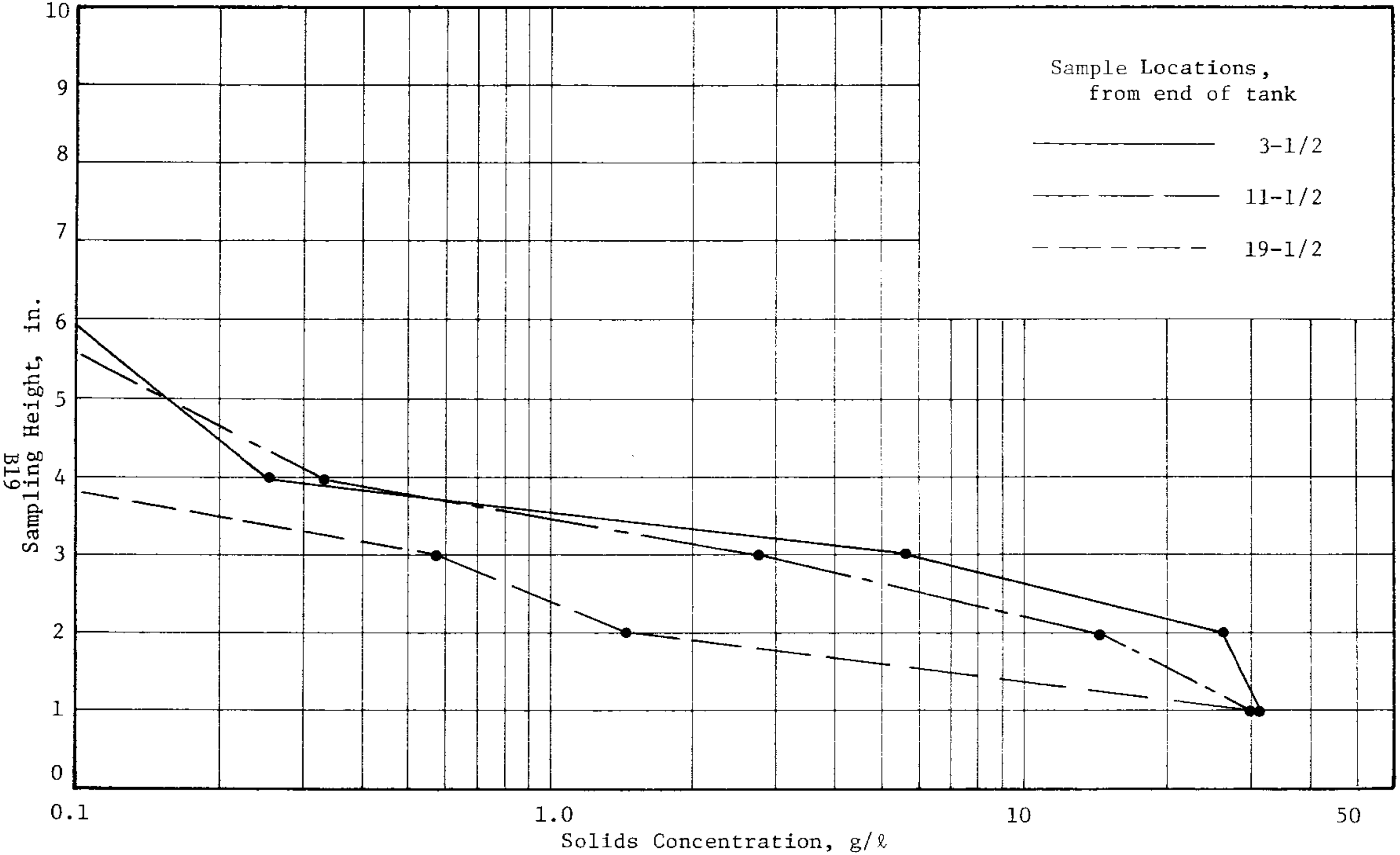


Figure B18. Concentration profiles, test 27

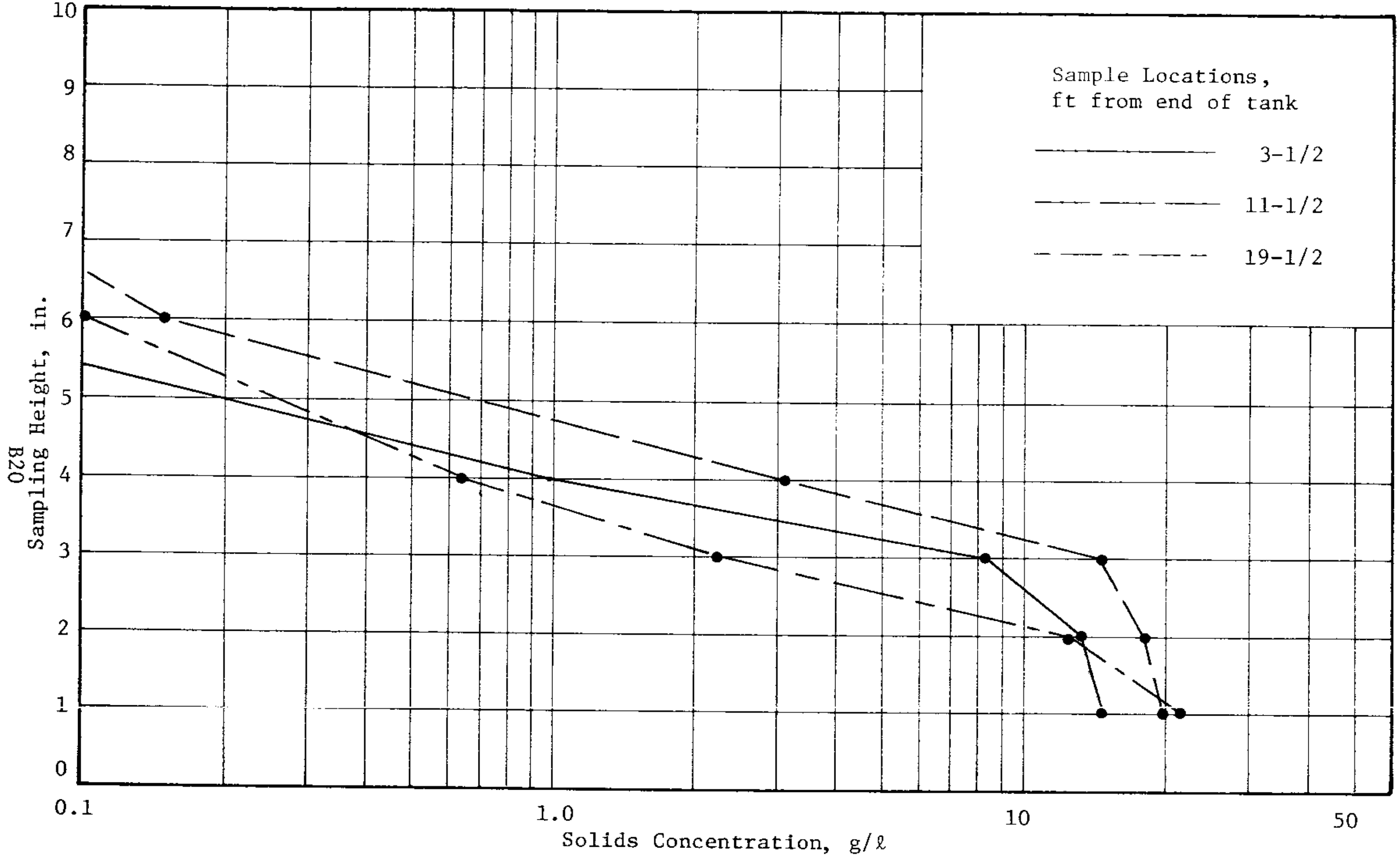


Figure B19. Concentration profiles, test 28

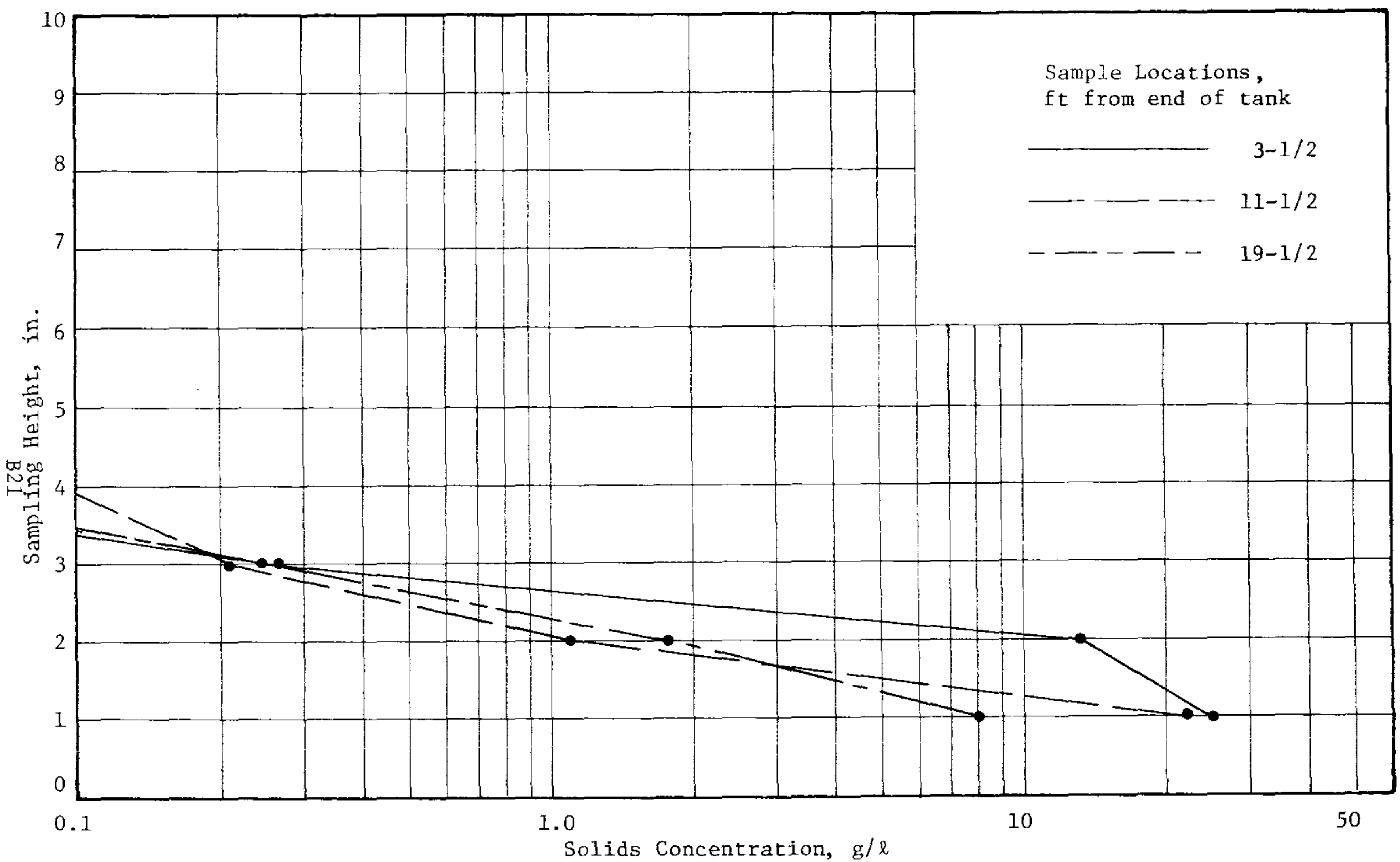


Figure B20. Concentration profiles, test 29

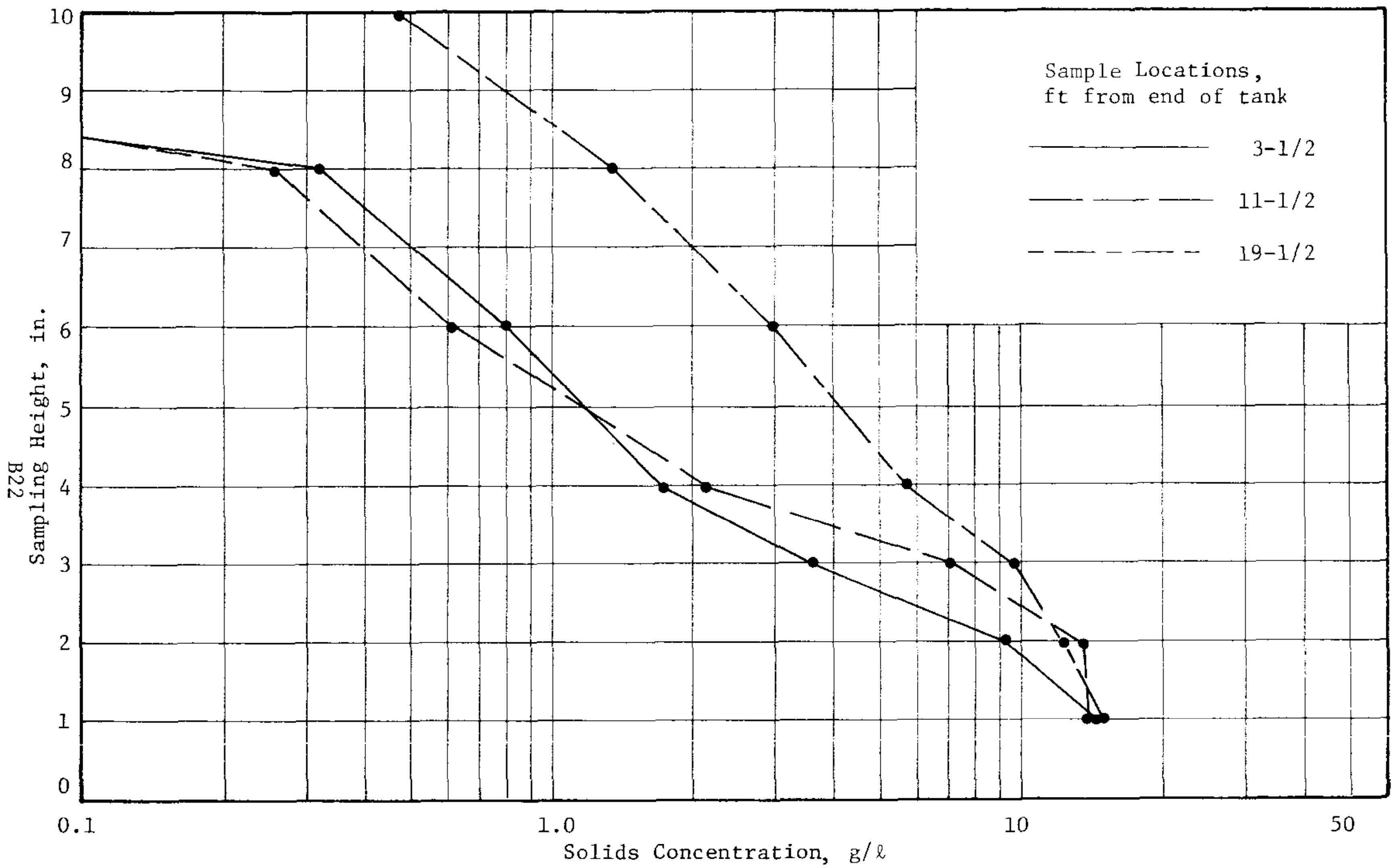


Figure B21. Concentration profiles, test 30

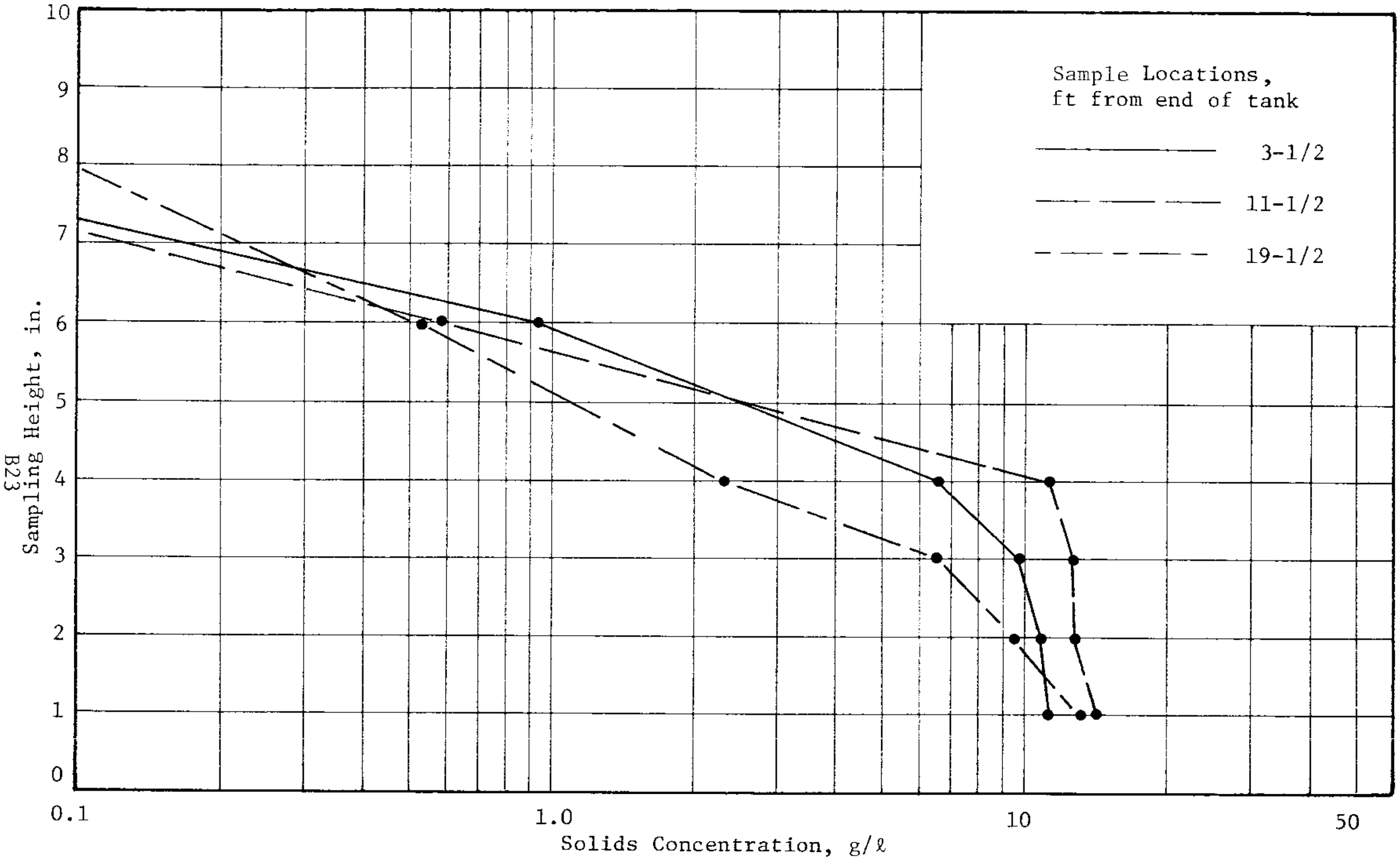


Figure B22. Concentration profiles, test 31

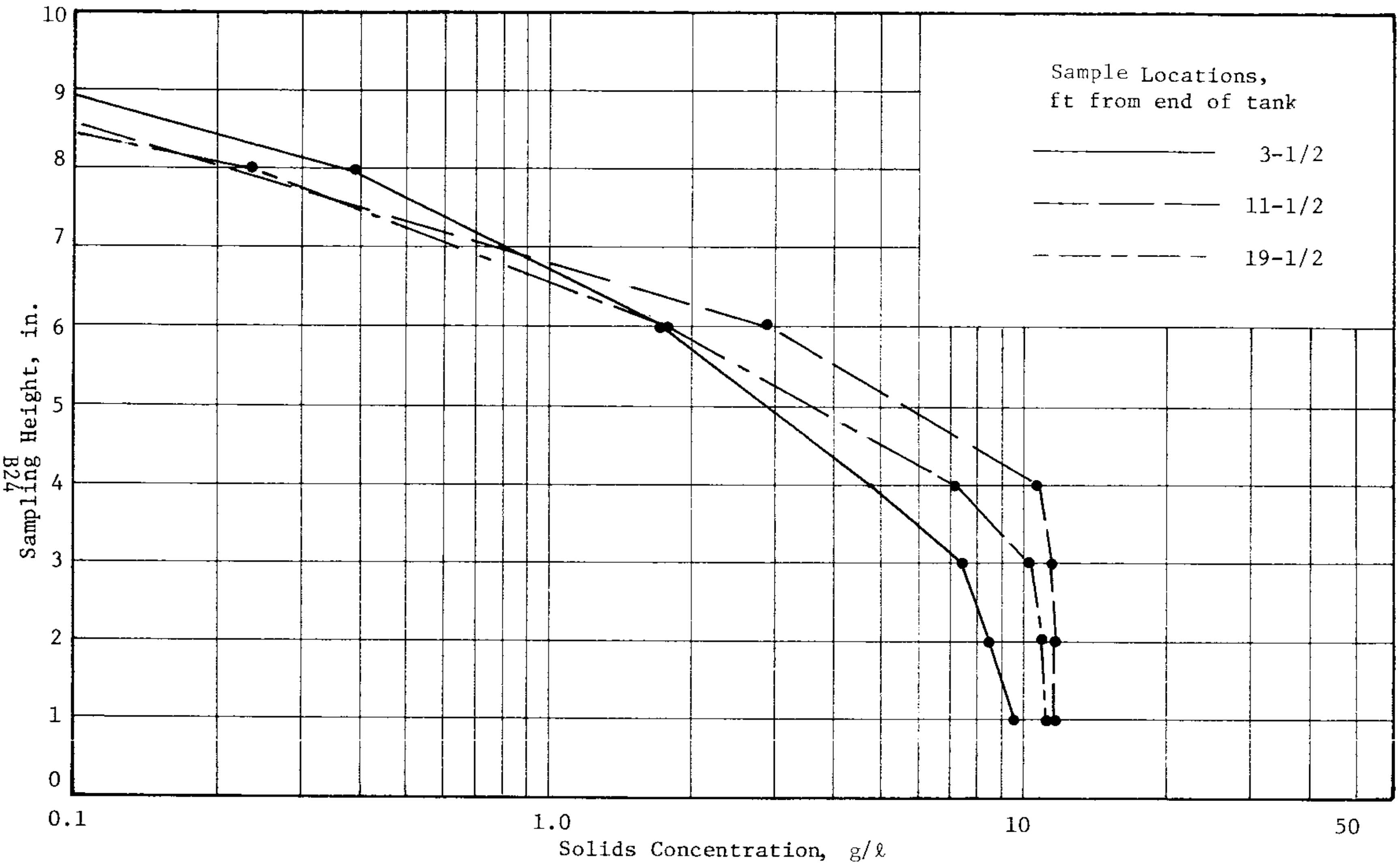


Figure B23. Concentration profiles, test 32

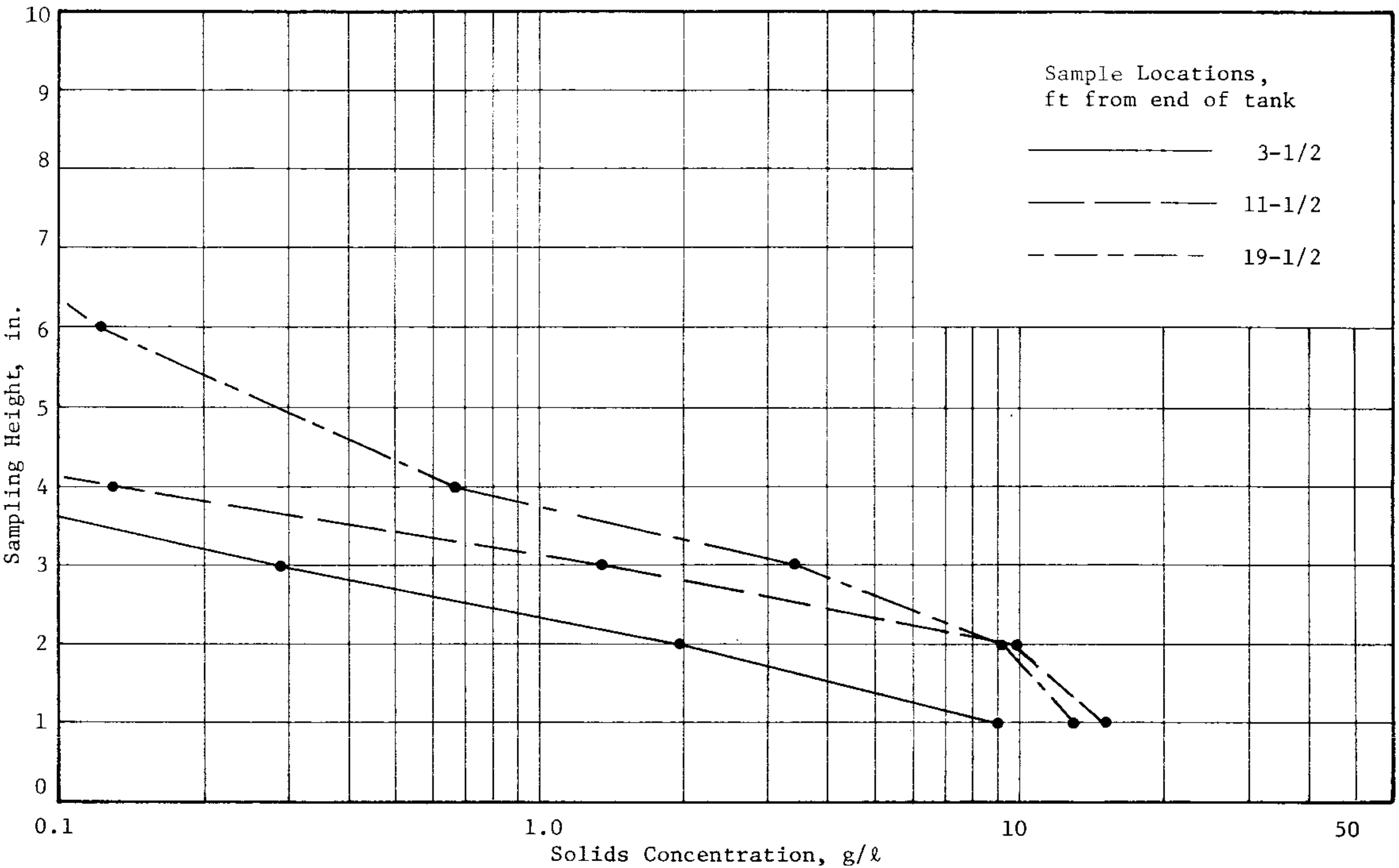


Figure B24. Concentration profiles, test 33

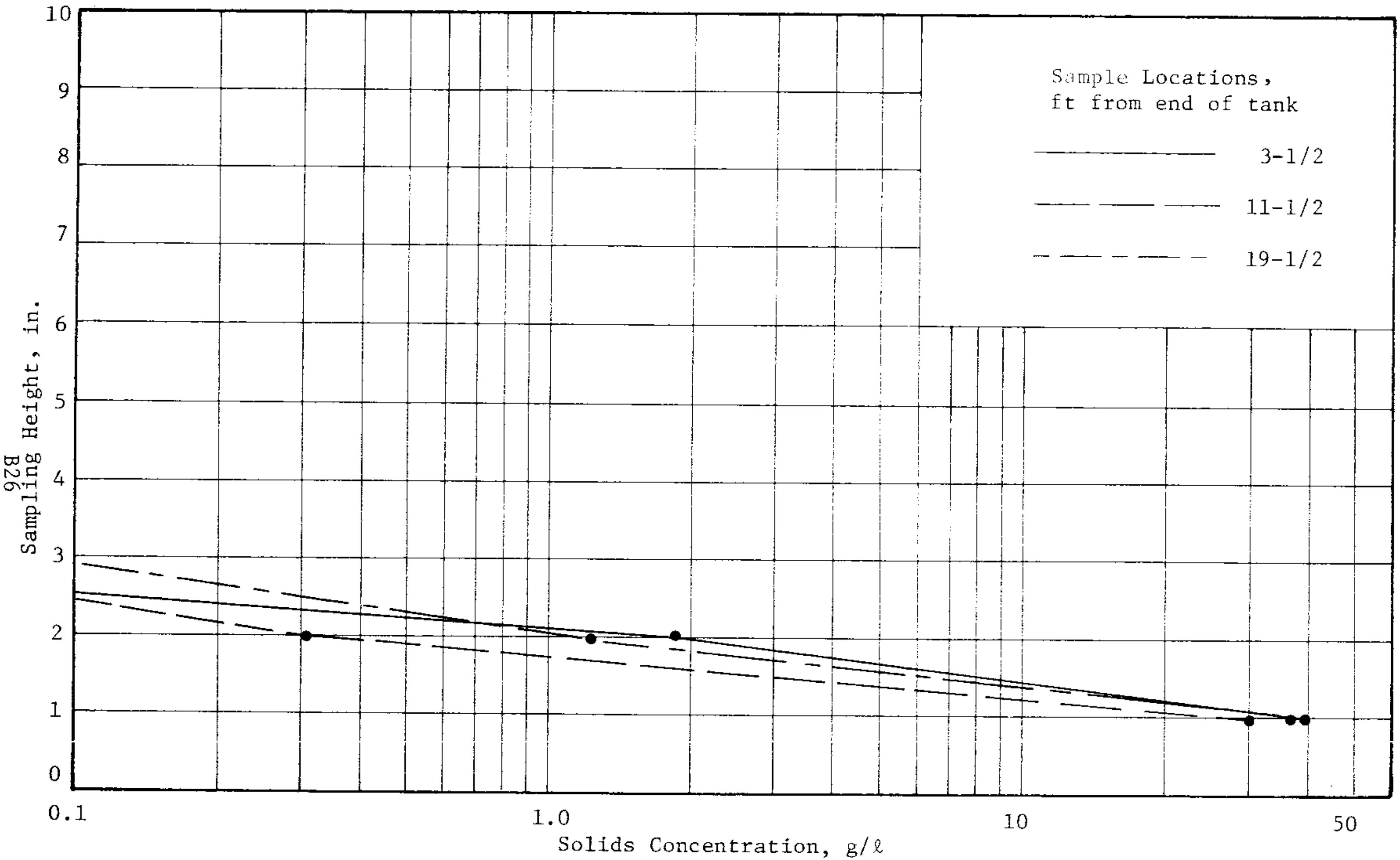


Figure B25. Concentration profiles, test 34

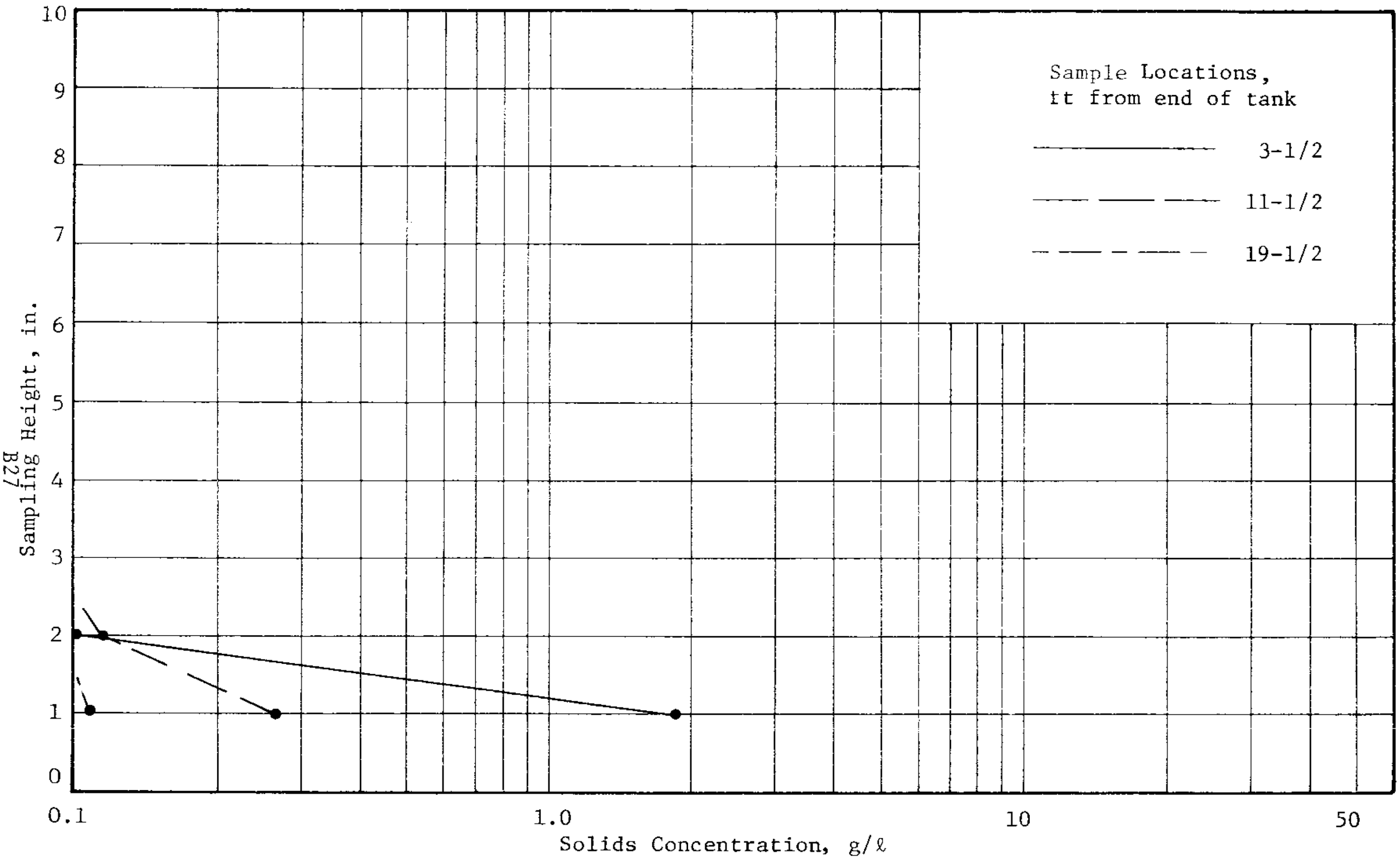


Figure B26. Concentration profiles, test 35

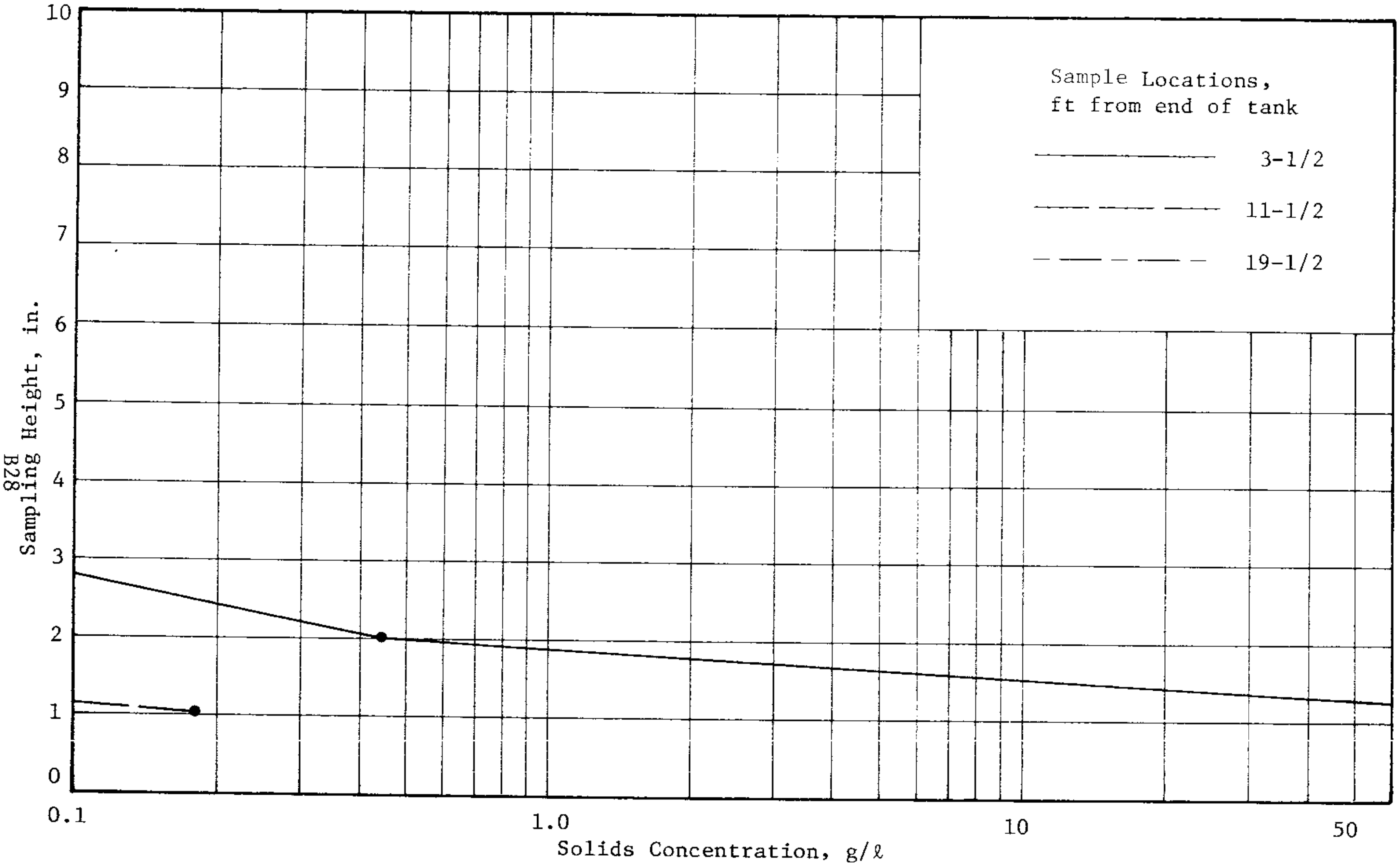


Figure B27. Concentration profiles, test 36

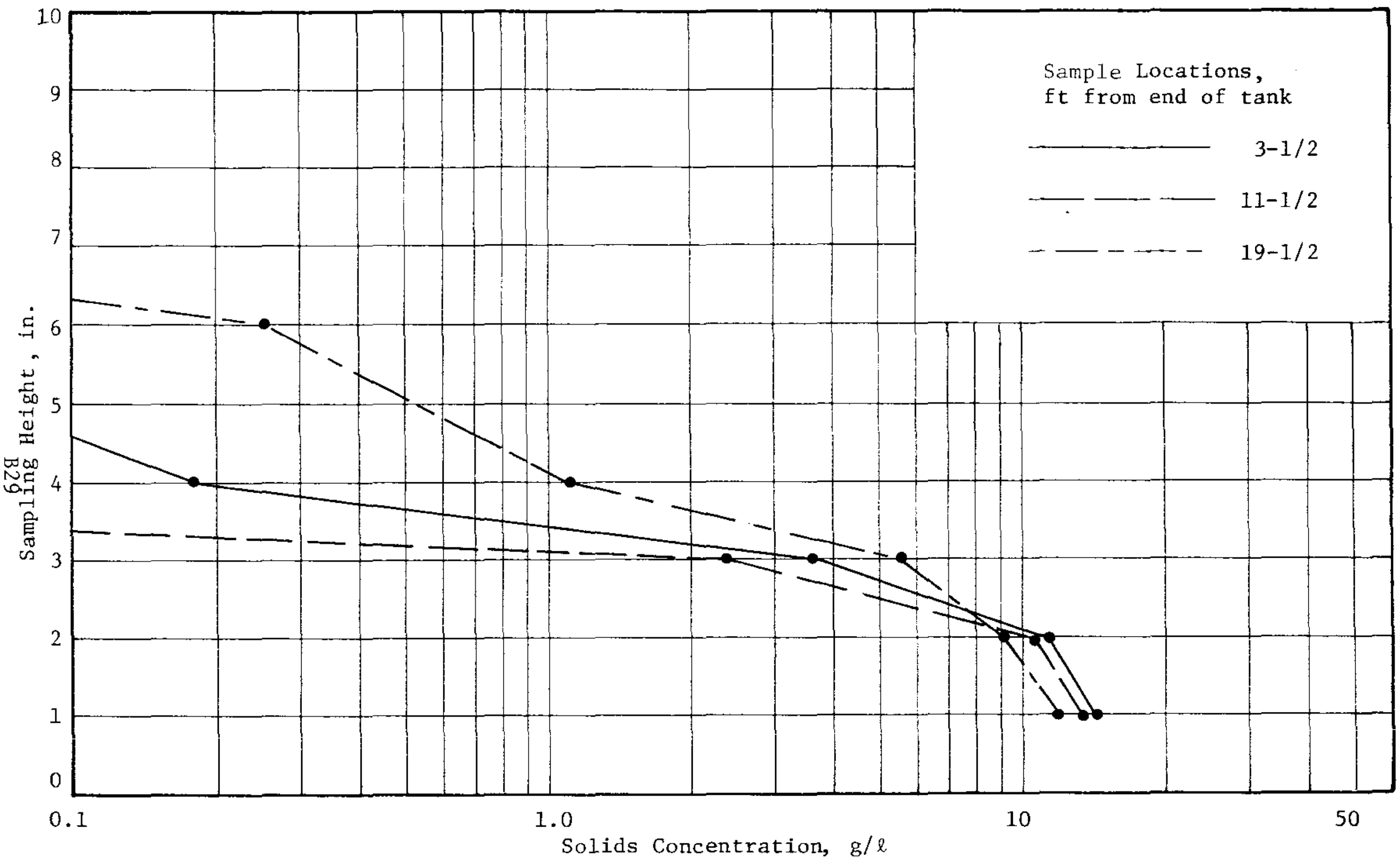


Figure B28. Concentration profiles, test 37

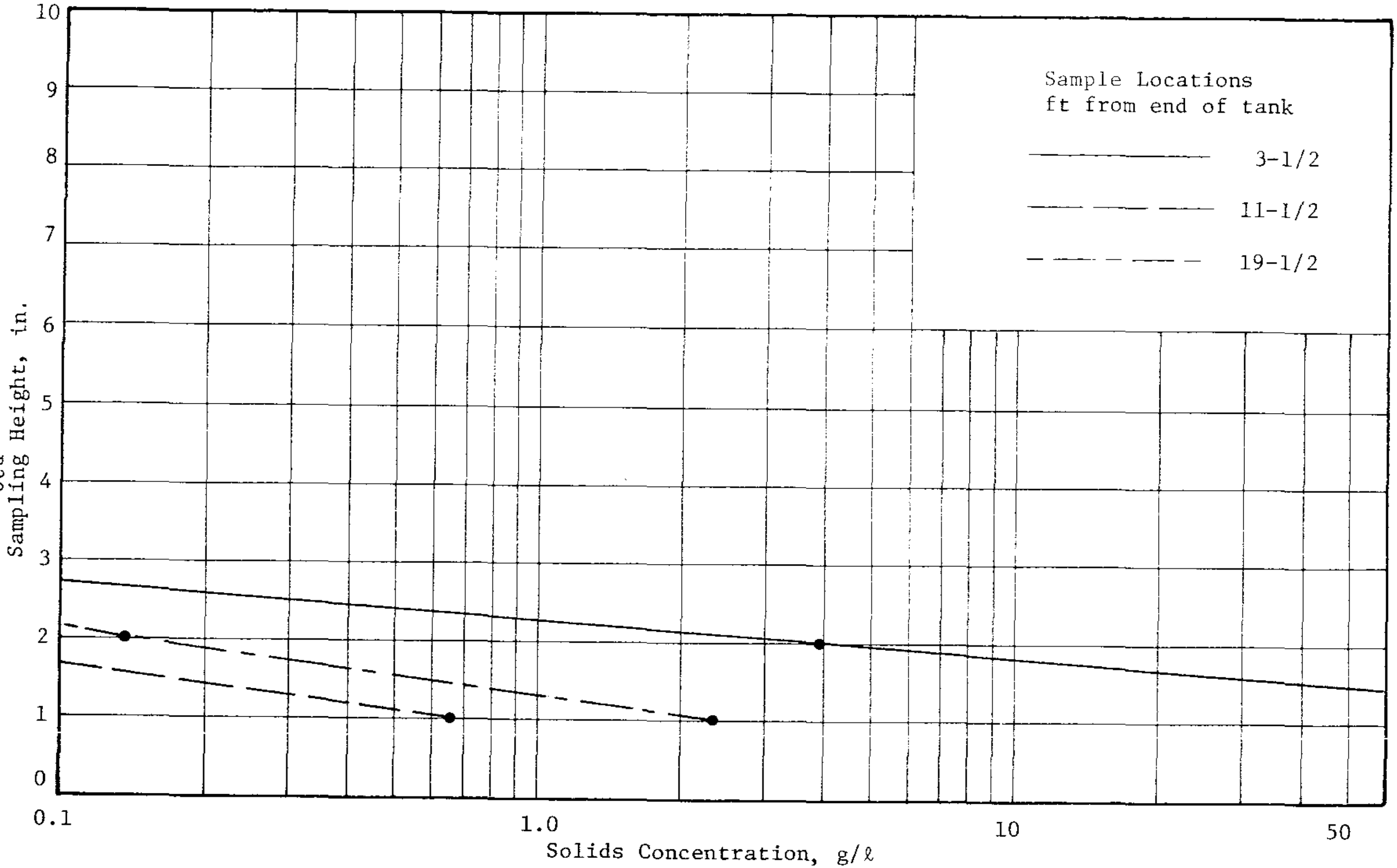


Figure B29. Concentration profiles, test 38

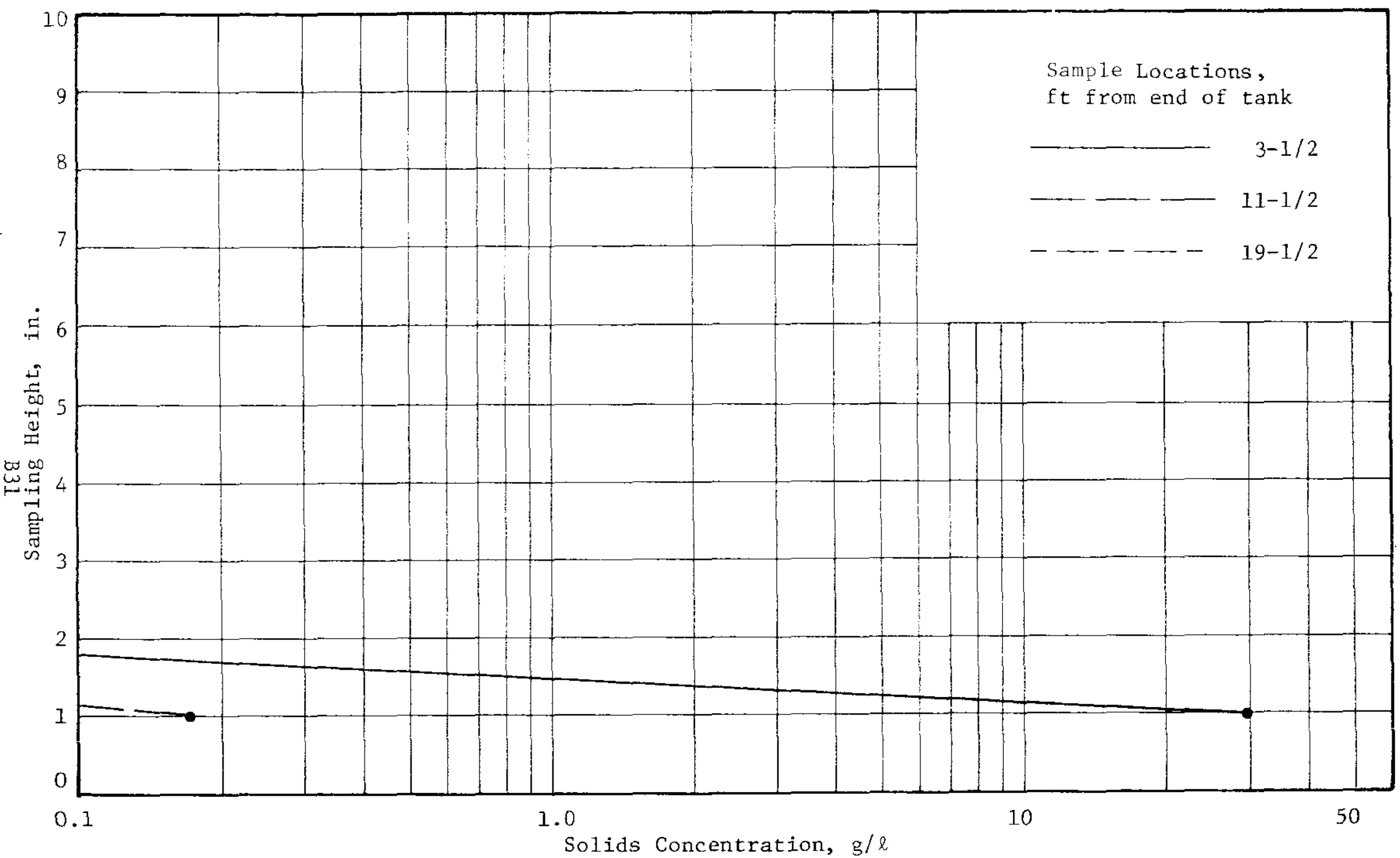


Figure B30. Concentration profiles, test 39

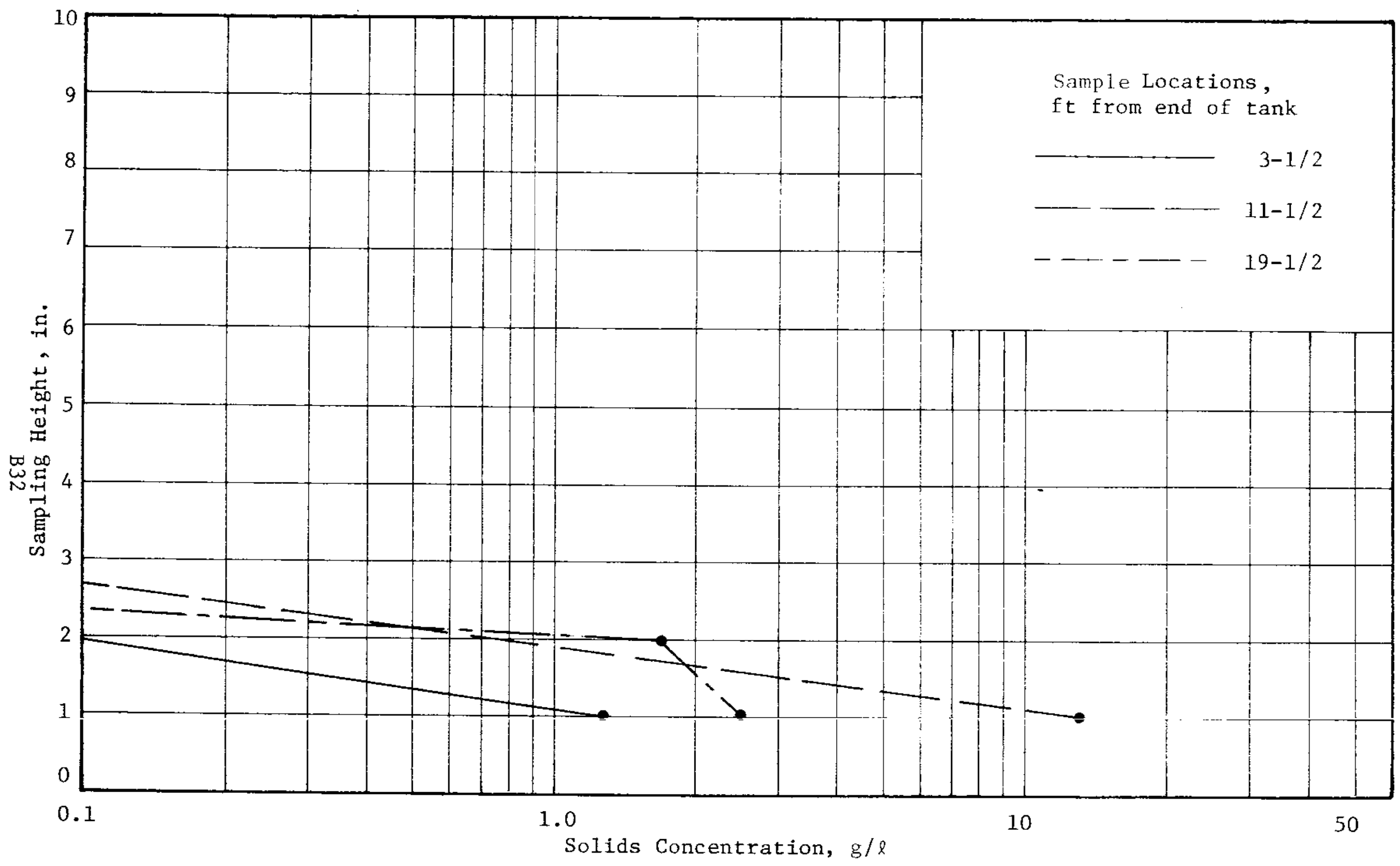


Figure B31. Concentration profiles, test 40

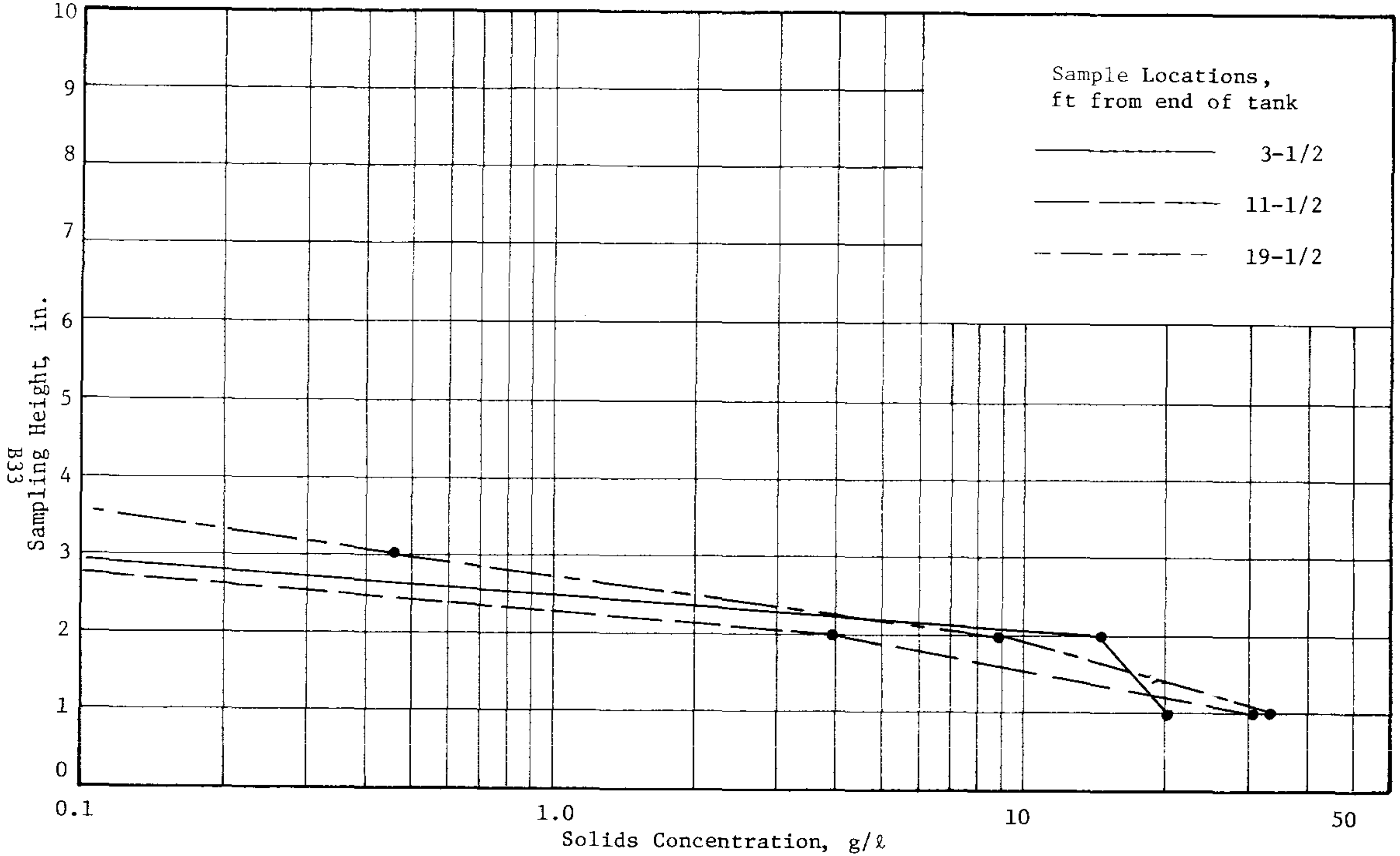


Figure B32. Concentration profiles, test 41

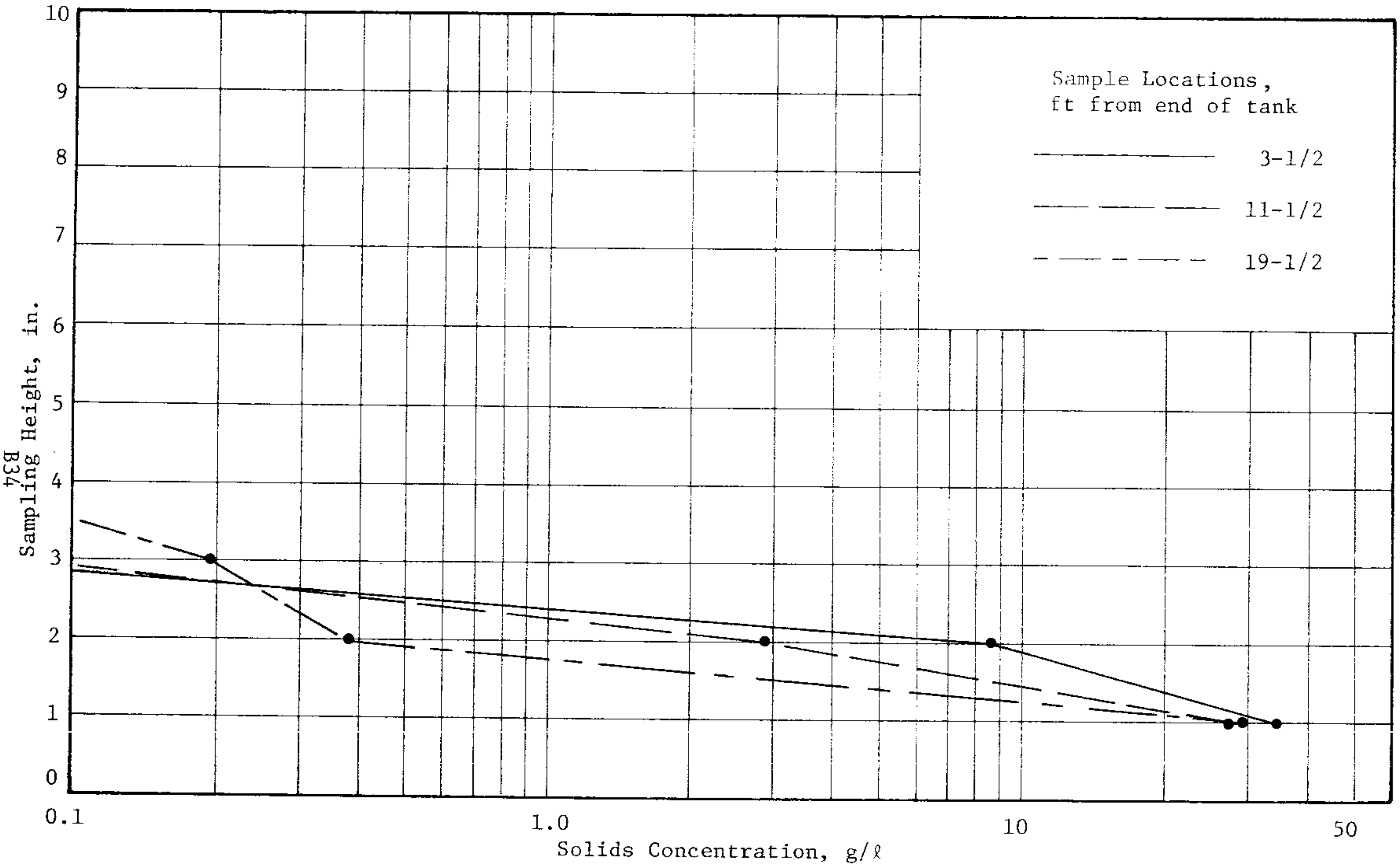


Figure B33. Concentration profiles, test 42

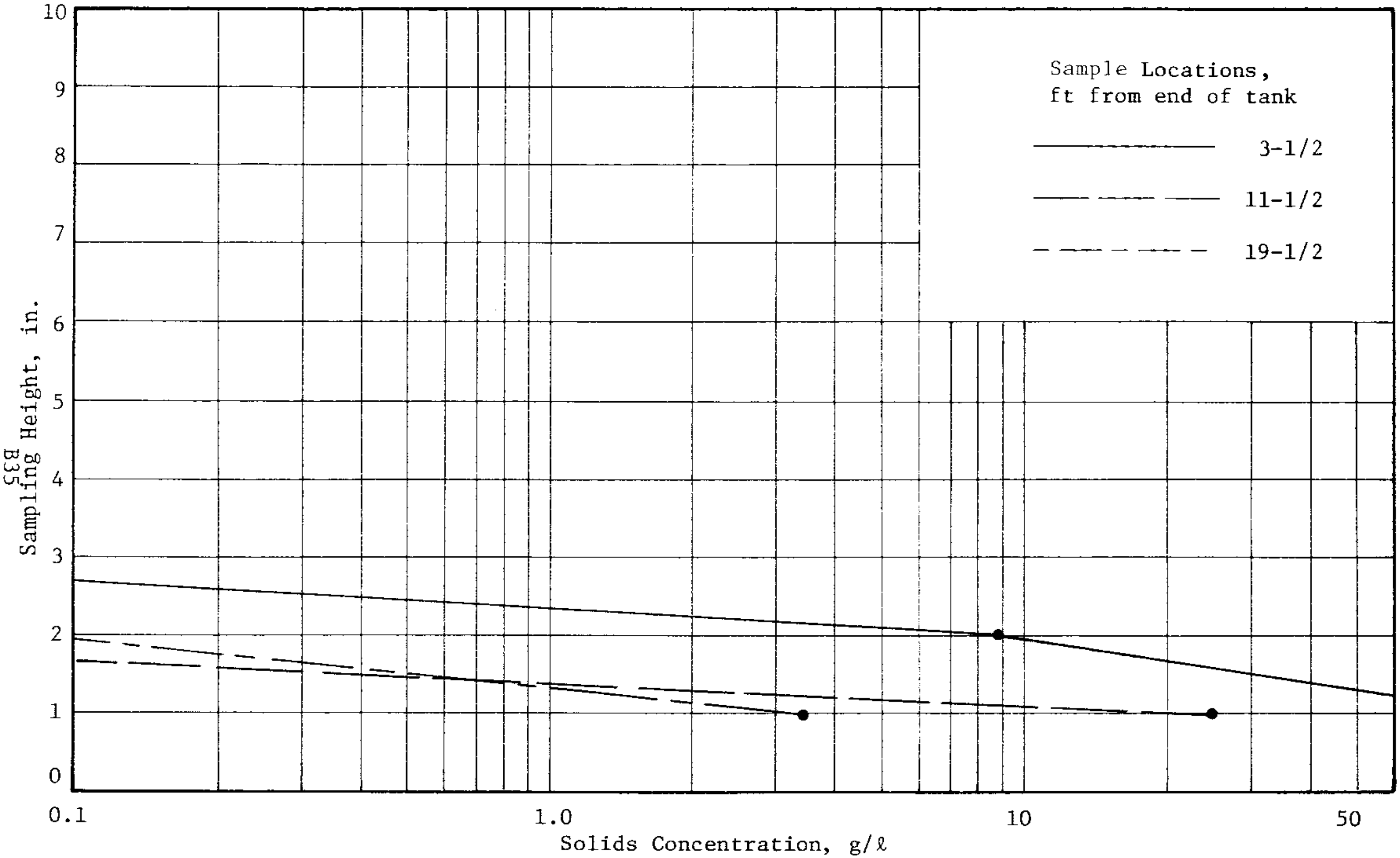


Figure B34. Concentration profiles, test 43

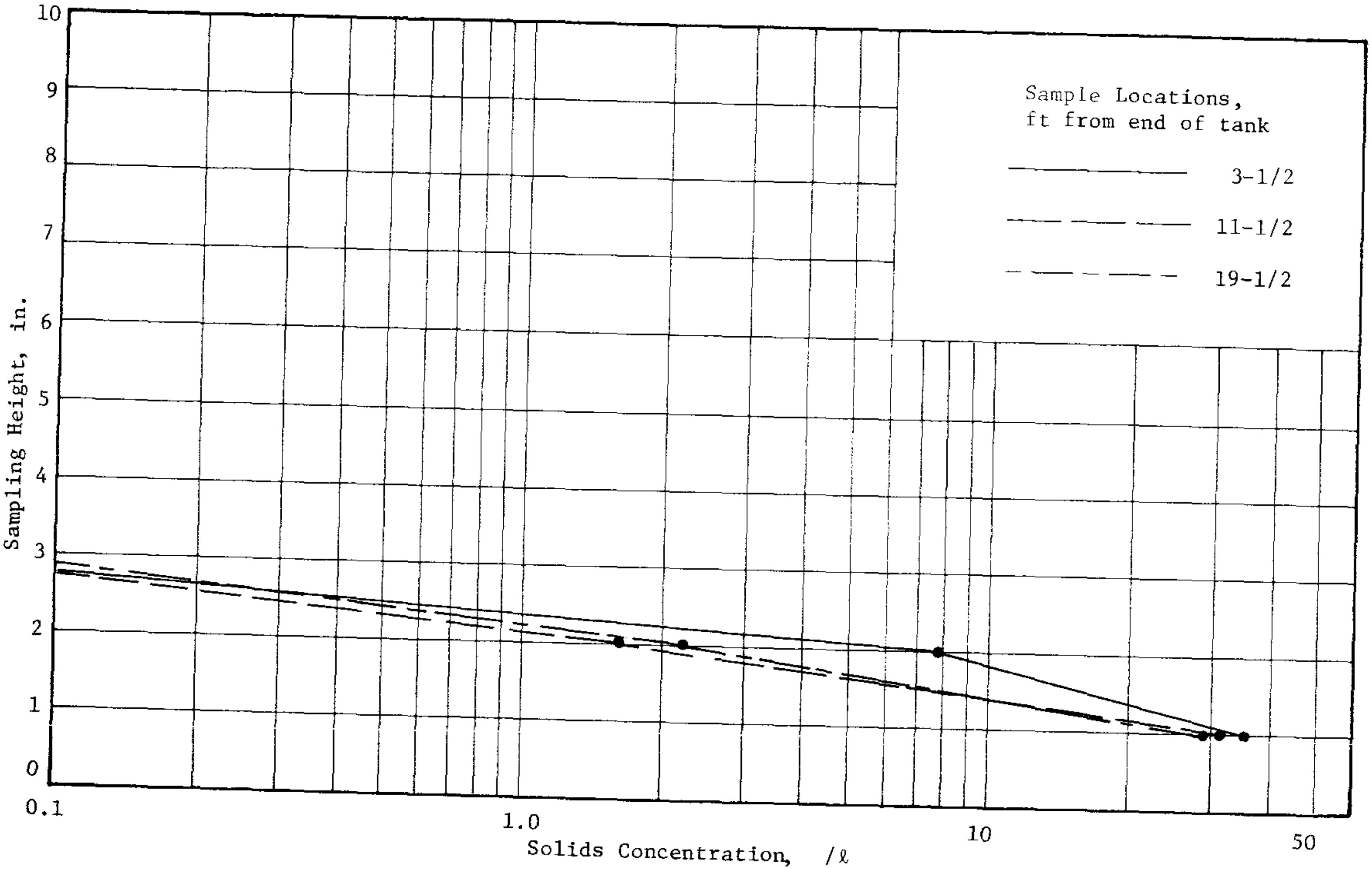


Figure B35. Concentration profiles, test 44

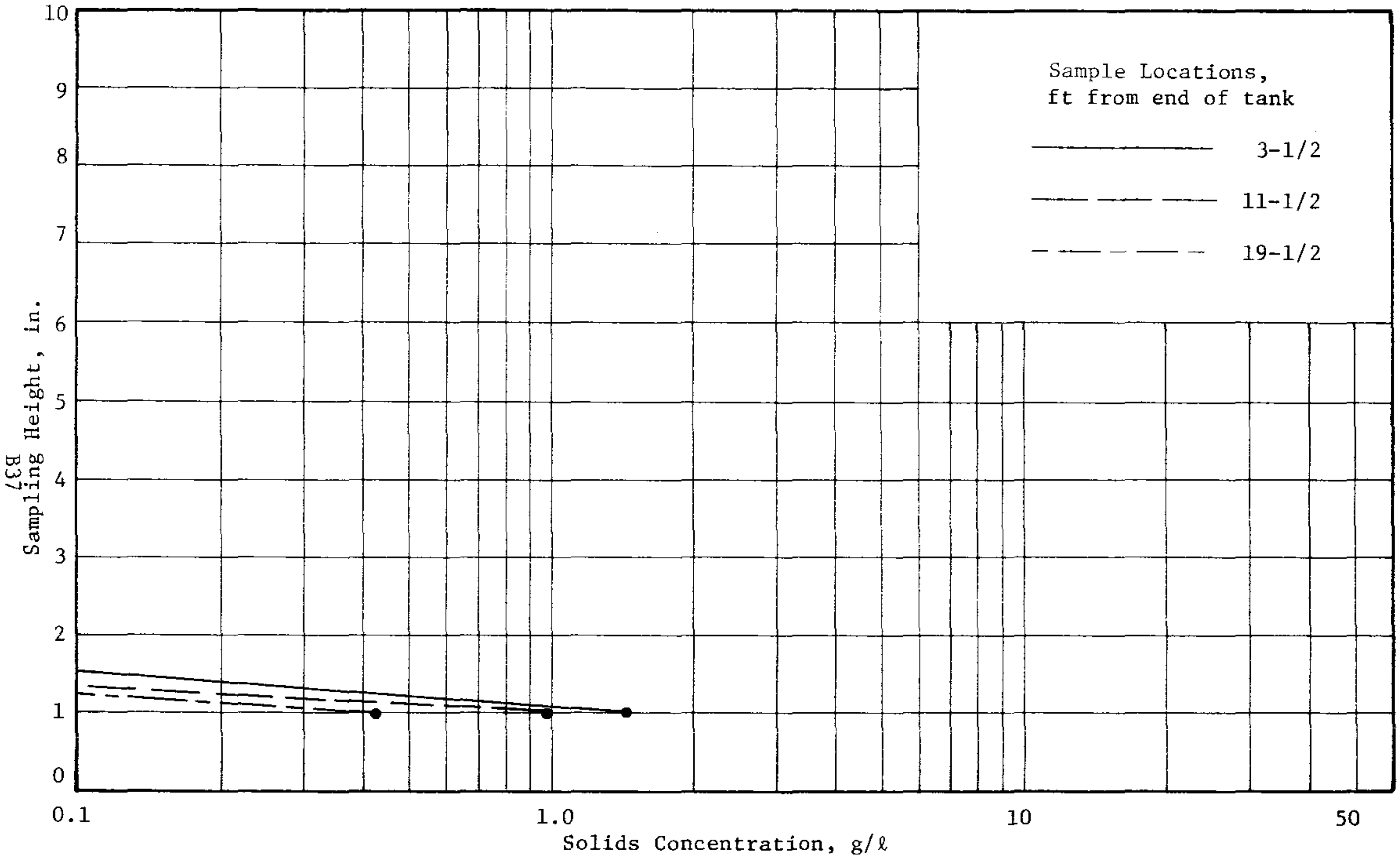


Figure B36. Concentration profiles, test 45

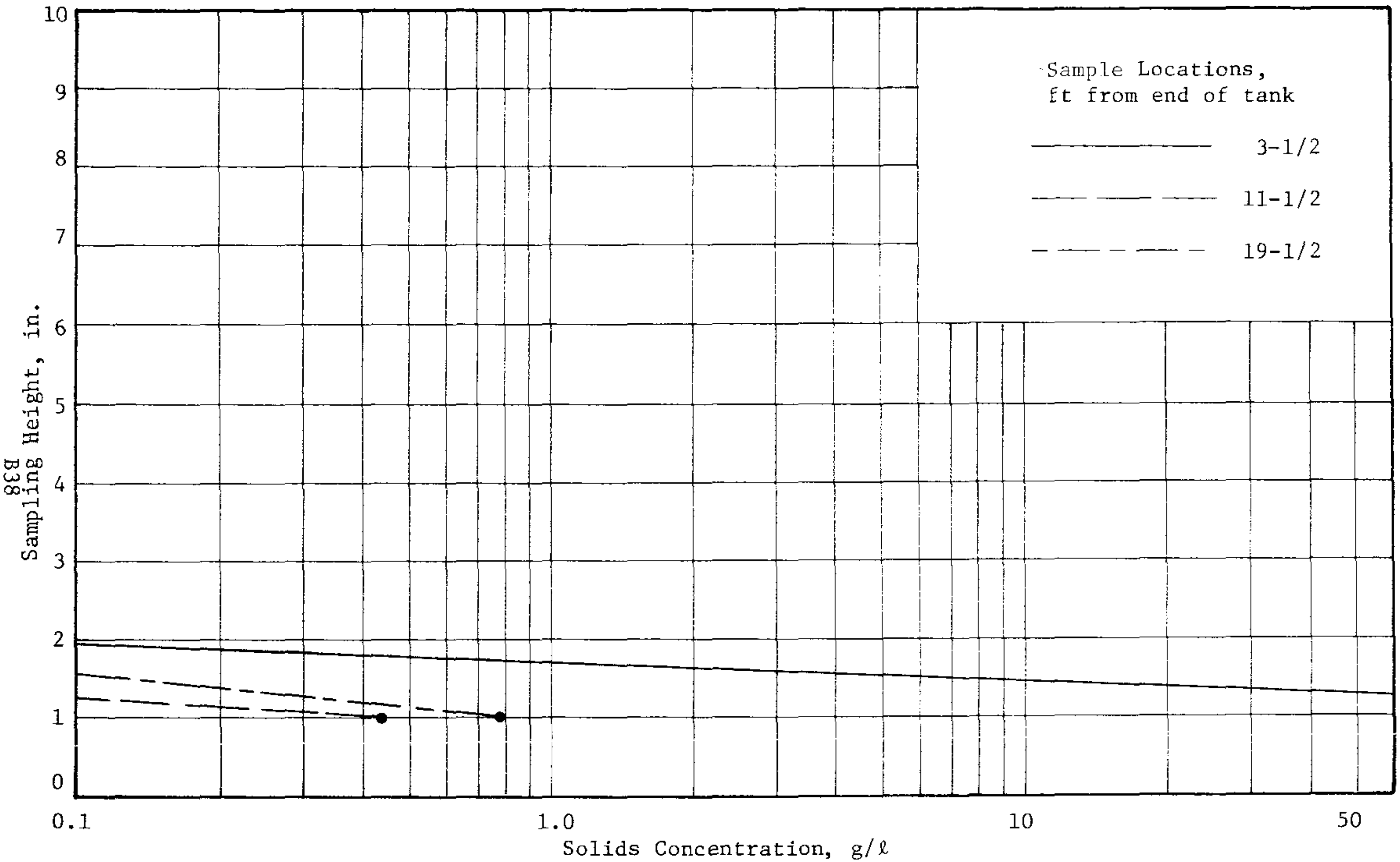


Figure B37. Concentration profiles, test 46

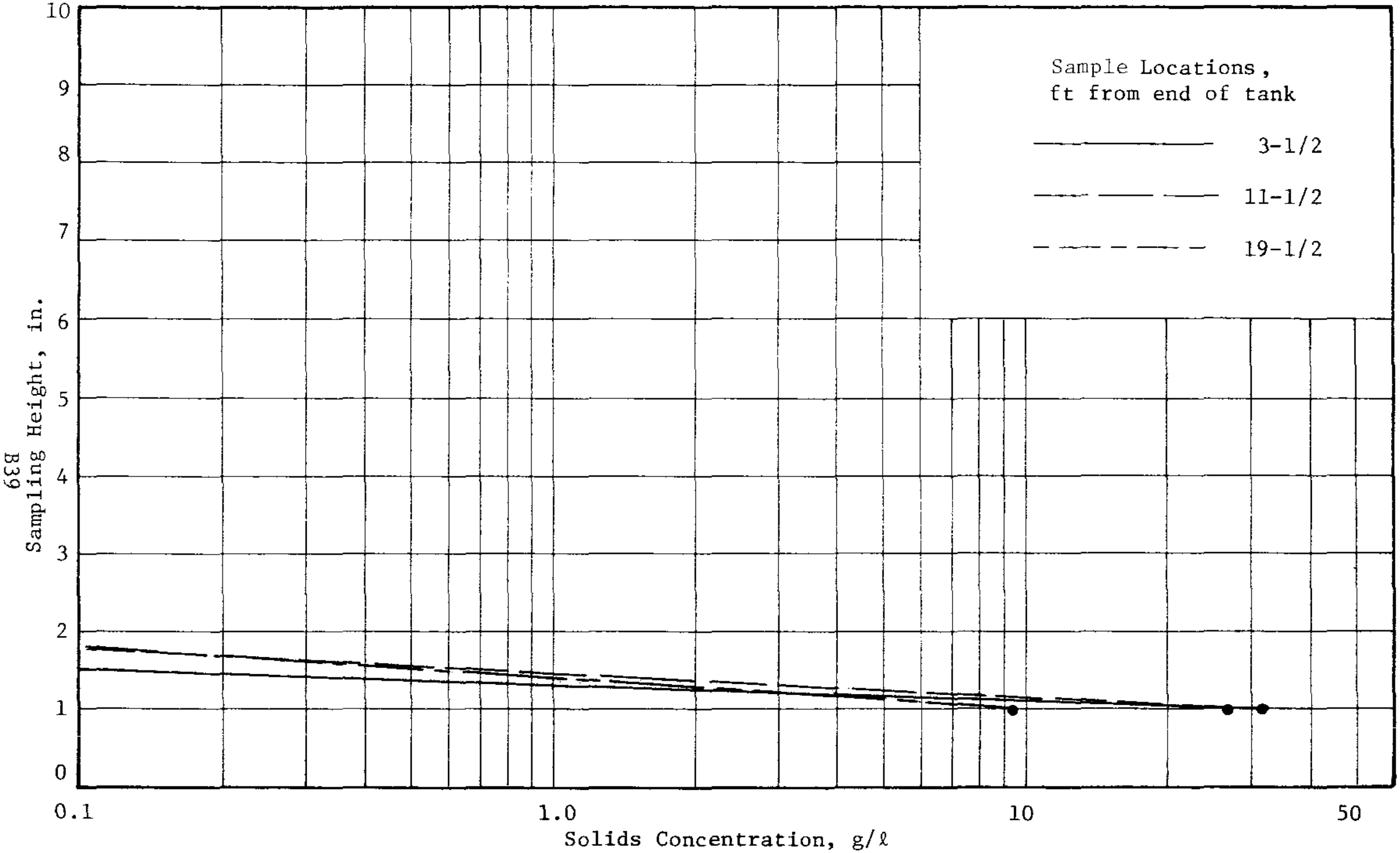


Figure B38. Concentration profiles, test 47

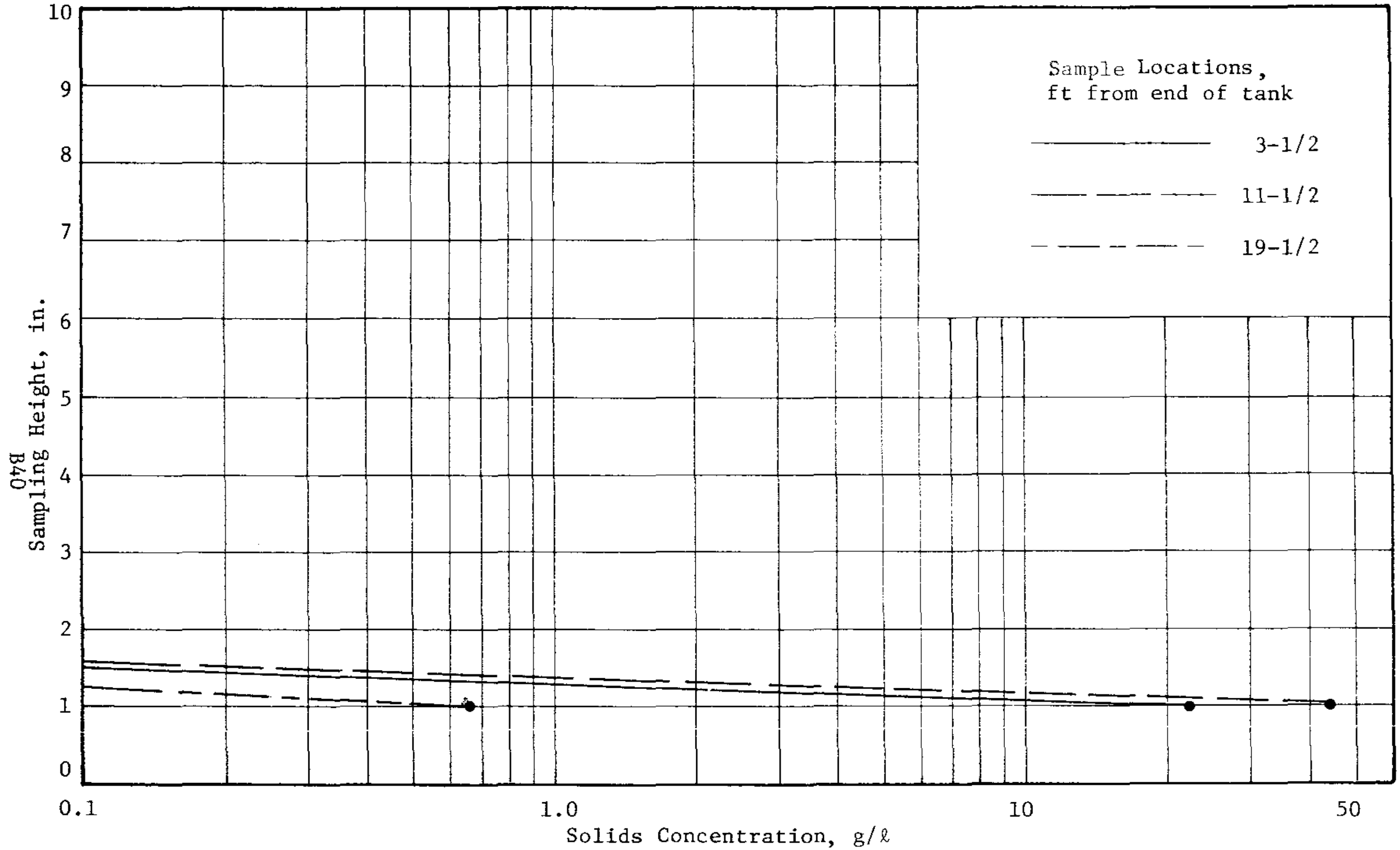


Figure B39. Concentration profiles, test 48

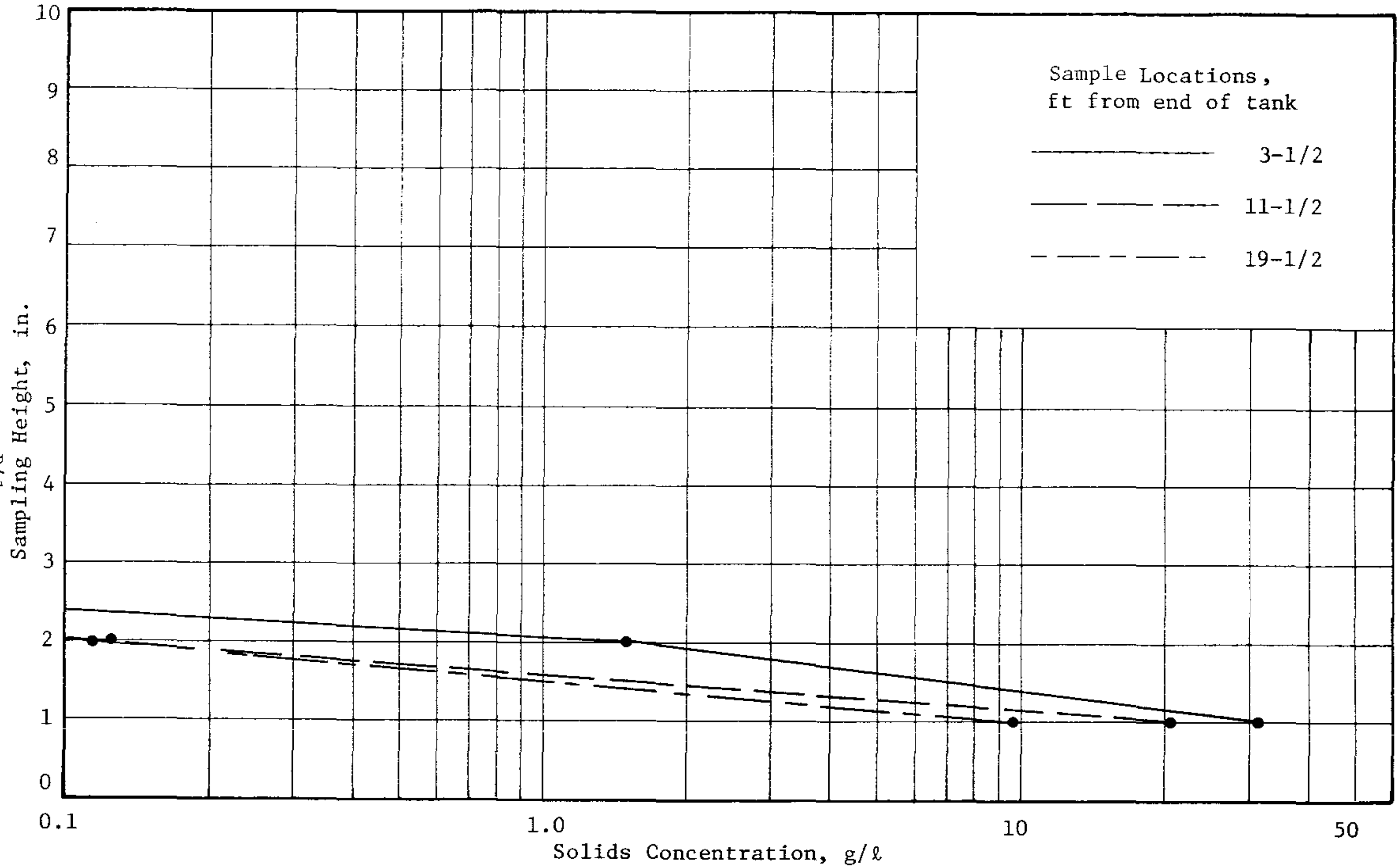


Figure B40. Concentration profiles, test 49

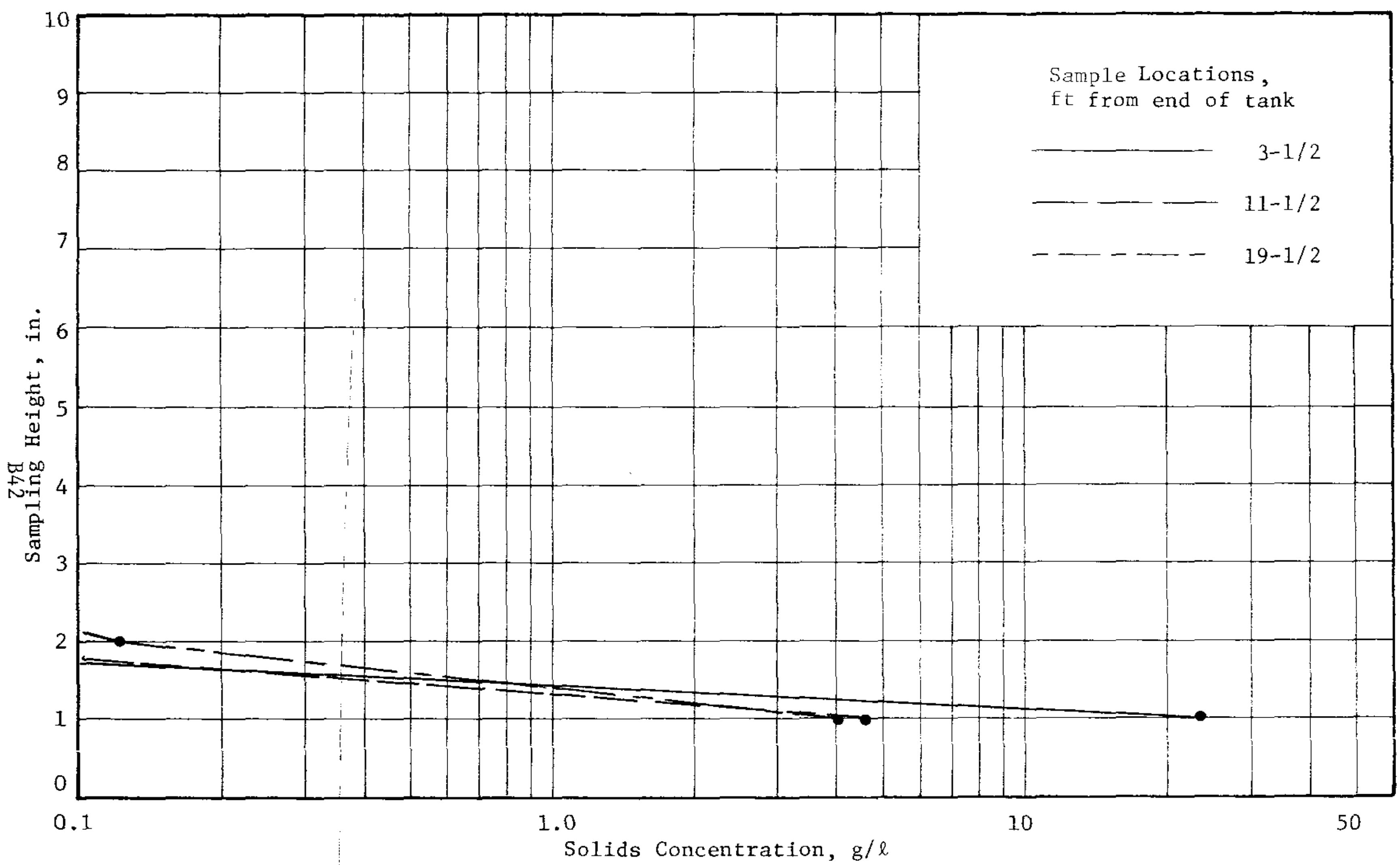


Figure B41. Concentration profiles, test 50

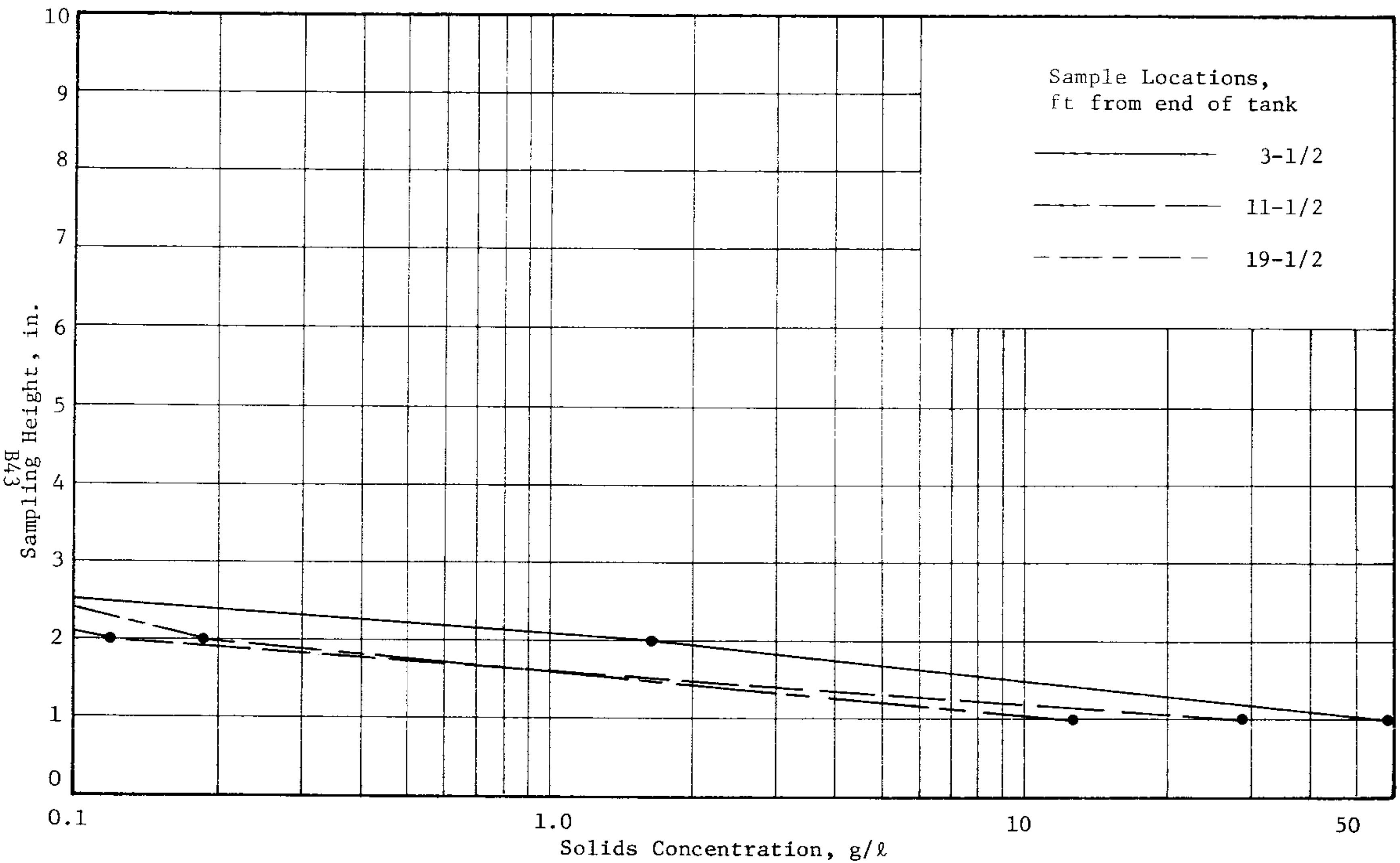


Figure B42. Concentration profiles, test 51

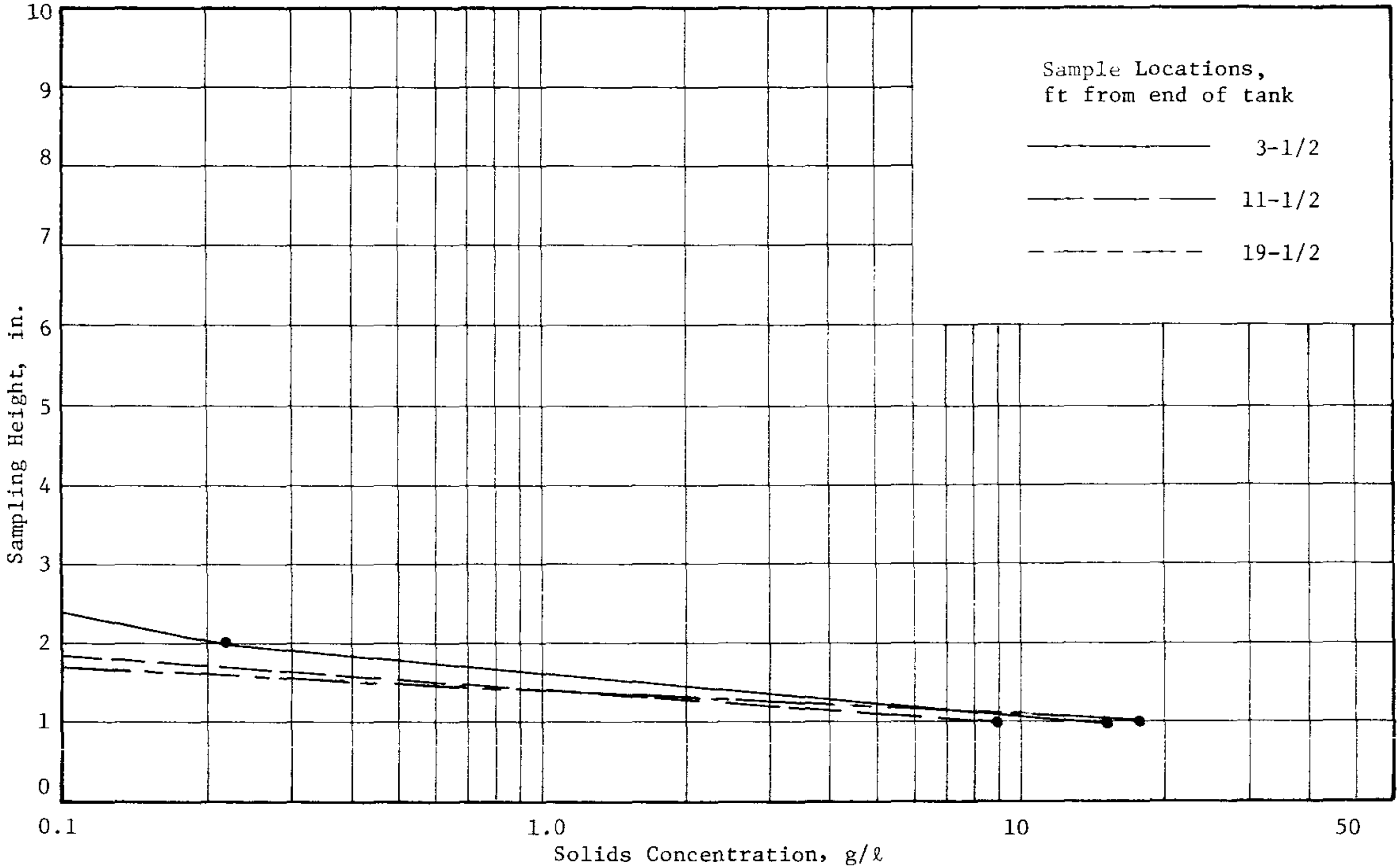


Figure B43. Concentration profiles, test 52

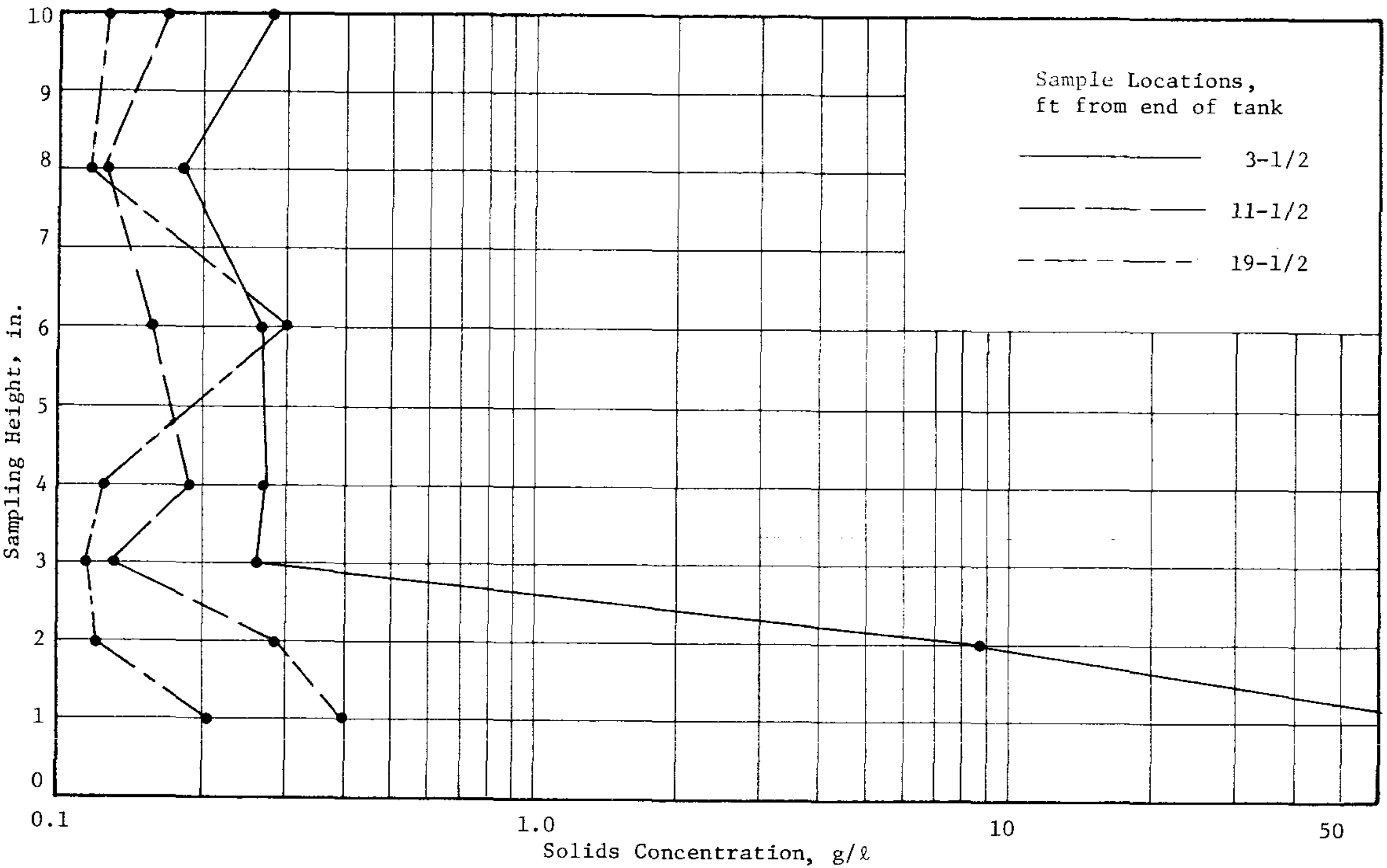


Figure B44. Concentration profiles, test 53

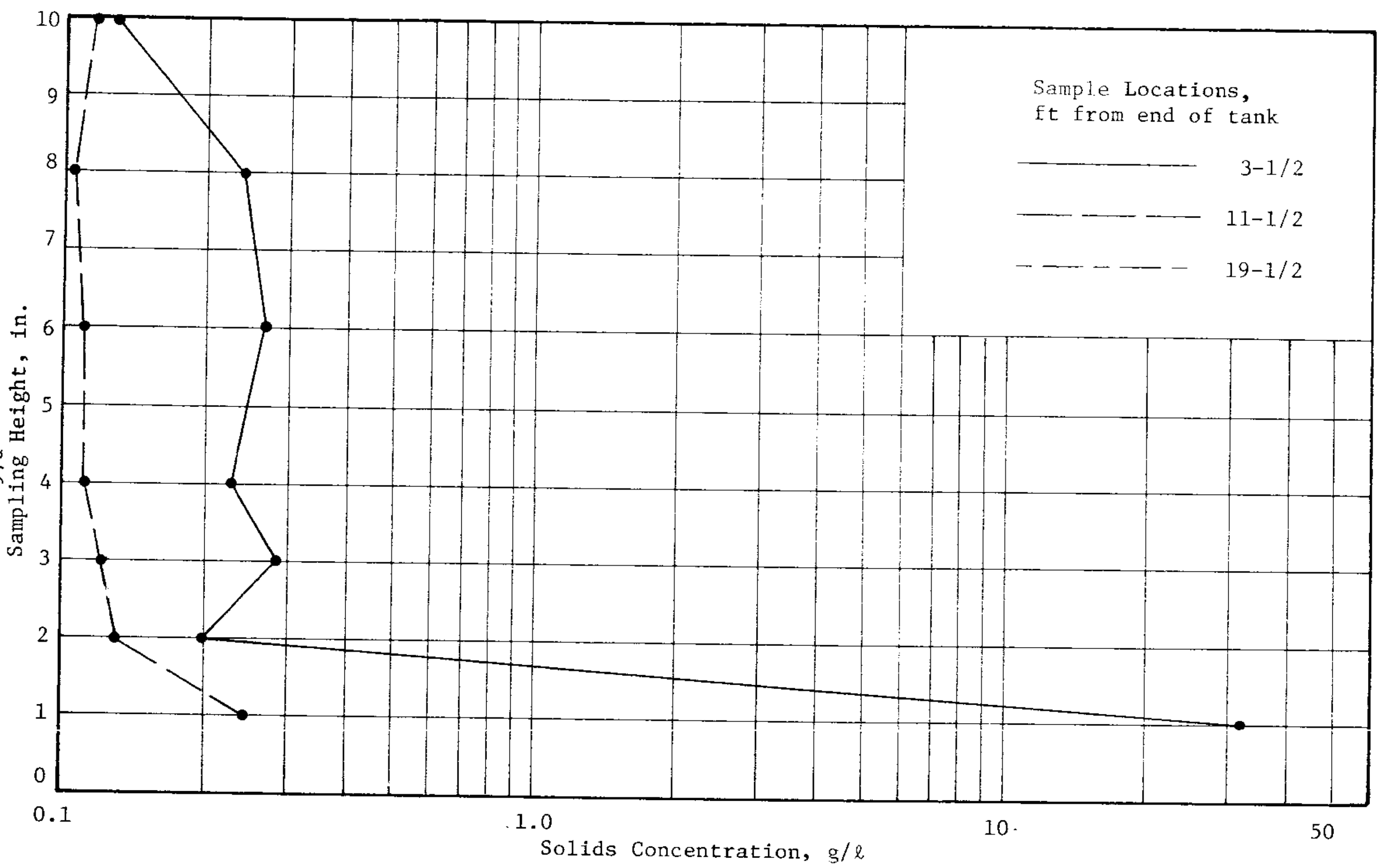


Figure B45. Concentration profiles, test 54

US GOVERNMENT PRINTING OFFICE: 1978-740-235/19

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Neal, Robert W

Evaluation of the submerged discharge of dredged material slurry during pipeline dredge operations / by Robert W. Neal, George Henry, Stephen H. Greene, JBF Scientific Corporation, Wilmington, Massachusetts. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.

176, 10, 46 p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; D-78-44)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACW39-76-C-0112 (Neg.) (DMRP Work Unit No. 6C08)

Literature cited: p. 176.

1. Dredged material. 2. Dredged material disposal. 3. Dredging. 4. Pipeline dredges. 5. Turbidity. 6. Underwater excavation. I. Henry, George, joint author. II. Greene, Stephen H., joint author. III. JBF Scientific Corporation. IV. United States. Army. Corps of Engineers. V. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; D-78-44.

TA7.W34 no.D-78-44